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# FACTORS AFFECTING ESTABLISHMENT OF DOUGLAS FIR SEEDLINGS

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## INTRODUCTION

Throughout the Douglas fir region of western Washington and western Oregon, one of the most productive forest regions in the United States, wide variation is observed in the rate and adequacy of natural restocking of forest land following deforestation by logging or fire or both. On some deforested areas a dense stand of reproduction soon appears, but others lie treeless for many years. The causes of this variation in restocking are not well understood.

Lands in the Douglas fir region that have been deforested since white settlement by logging or fire or both total approximately 11 million acres.[2] It is estimated that at least 20 percent of this enormous area, although logged or burned prior to 1920, has failed to reforest at all, and that an additional 50 percent has failed to restock sufficiently well to assure a full forest crop. Furthermore, logging and slash burning are constantly increasing the area in need of reseeding, and at the same time are removing or reducing the seed supplies. Logging activities also lead to repeated uncontrolled fires, which destroy remaining seed trees and much young growth. On some of the cut-over areas where seed supplies are adequate, large numbers of Douglas fir (*Pseudotsuga taxifolia* (Lamb.) Britt.) seedlings germinate but die because of unfavorable environmental conditions.

The purpose of the study discussed herein is to measure what appear to be the governing environmental factors on typical logged and slash-burned areas in a given locality, and to correlate the resultant measurements with Douglas fir seedling establishment or failure; that is, to determine the causes of the high seedling mortality frequently observed, in order that steps may be taken to reduce this loss. The portion of the study covered by this circular was carried on from 1927 to 1931, inclusive, on lands in the vicinity of the Wind River Experimental Forest of the Pacific Northwest Forest Experiment Station, near Carson, Wash. These lands lie near the geographic center of the Douglas fir region.

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[1] Technical assistants who helped with the field work of the study were E. C. Loy, J. C. H. Robertson, D. Janzen, W. G. Morris, and H. Fowells.

[2] PACIFIC NORTHWEST FOREST EXPERIMENT STATION. Forest Research Notes No. 13, 13 pp. 1934. [Mimeographed.] The figure given does not include lands devoted to agriculture.

## REVIEW OF LITERATURE

The influences of environmental factors on tree-seedling establishment have received the attention of numerous investigators in this country and abroad, but comparatively little research in this field has been done on Douglas fir in the Pacific Northwest. For the sake of brevity, references will be limited to certain American works that have a definite bearing on this subject.

Hofmann (*9*) [3] made a study on Douglas fir in the Pacific Northwest, principally in the same general locality in which the present study was made, during a 10-year period beginning in 1913. He stated that a surface-soil temperature of 144° F. had been found to kill Douglas fir seedlings. On a south slope near the Cispus River he measured surface-soil temperatures as high as 135°. On a southerly exposure in the Wind River Valley he found a surface-soil temperature of 129.4° and a soil-moisture content of 11.2 percent at a 6-inch depth, as compared with a surface-soil temperature of 82.4° and a soil-moisture content of 17.5 percent at a 6-inch depth on a similar north exposure. Hofmann stated that "the actual killing of young growth by frost is not common, but the death of seedlings as the result of heaving by frost is often extensive."

Hartley (*8*), having made observations in 1909 on deaths of pine seedlings in nursery beds at Halsey, Nebr., resulting from stem lesions which he distinguished from those of the common damping-off disease and called "white spot," and having later produced such lesions artificially, arrived at the theory that this injury was due mainly to excessive heat.

Bates (*5*), reporting on a study in the Rocky Mountain region, stated that surface-soil temperatures of 150° F. and occasionally 160° occur on south exposures on warm summer days, and that tender plant tissue such as that of very young tree seedlings is killed almost instantly if heated to 140°. At the Fremont Experiment Station (Colorado Springs, Colo.), Bates (*4*) found that the maximum surface-soil temperature was greater by 60° on a 45-percent south slope than on the coolest neighboring site. In a locality where Engelmann spruce (*Picea engelmanni* Engelm.), ponderosa pine (*Pinus ponderosa* Dougl.), and Douglas fir were present he found, also, that heat tolerance and immediate deep rooting were important among factors determining which species should predominate on a given area.

Alexander (*1*), presenting findings from a study of first-year mortality of Douglas fir in the "fog belt" of the Pacific coast, named high soil temperature as the cause of 78 percent of the deaths on bare mineral soil and of 86 percent of those on an unshaded spring burn.

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[3] Italic numbers in parentheses refer to Literature Cited, p. 44.

Baker (*2, p. 973*) stated:

> The living tissues of seedlings of representative conifers of western America (1–3 months old) are quickly killed when a temperature of about 54° C. (130° F.) is reached but can withstand a temperature only a few degrees lower for some time. * * * injury has been noted with maximum temperatures as low as 120° F.

The temperatures referred to by Baker are internal temperatures. In the study on which he based these statements he grew seedlings in pans and pails in dark adobe soil overlaid with coarse sand, pierced them with thermocouples, and exposed them to heat from an electric heater.

Toumey and Neethling (*18*), studying heat injury to seedlings of northern white pine (*Pinus strobus* L.), white spruce (*Picea glauca* (Moench) Voss), and eastern hemlock (*Tsuga canadensis* (L.) Carr.), found that heat lesions "may appear in young coniferous seedlings whenever the temperature of the topsoil exceeds 122° F."

Toumey (*17*), working at Keene, N. H., found that after midsummer the soil of a denuded area, sampled to a depth of 3 feet, remained on the whole much more moist than that of a forested area; even the upper 4-inch layer, at critical periods of late summer, had as much available moisture as the forested soil, or more. He found evidence, also, that poor condition and poor growth of natural reproduction of northern white pine were due to inadequacy of soil moisture at critical periods during the growing season and to mulch effect rather than to inadequacy of light.

Li (*12*), at Keene, N. H., found evidence that ground water played a very insignificant part in supplying the needs of seedlings, as during the dry-weather period in that locality the 0- to 9-inch layers of soil were more moist than the 9- to 27-inch layers.

Pearson (*13*), working in the Southwest with Douglas fir, ponderosa pine, Engelmann spruce, and bristlecone pine (*P. aristata* Engelm.), found little difference among species in rate of transpiration and power to extract water from the soil, and attributed species differences in seedling survival under natural conditions principally to differences in rooting habits. Pearson (*14*) found also that the natural ranges of different tree species in the Southwest are limited by requirements as to temperature and moisture.

Craib (*6*), at Keene, N. H., found that at a depth of 0 to 10 centimeters the forest soil permitted seepage of surface water more than twice as rapid as that permitted by the soil on a denuded area.

Barr (*3*), working with spruce (*Picea* spp.), found very much better germination on mineral soil than on humus soil, but better survival on humus soil.

Shreve (*16*), investigating soil temperature at a 3-inch depth on different exposures at elevations of 3,000 to 5,000 feet near Tucson, Ariz., concluded that:

> Insolation is of more importance than air temperature in determining the temperature of the soil. * * * The difference between the vegetation of north and south slopes is due to a group of conditions initiated by the differences in insolation and soil temperature existing on them. Maximum soil temperatures show more difference than minima with differences of either altitude or slope exposure.

Roeser (*15*), studying reproduction in a forest chiefly of Douglas fir in Colorado, in which one plot had been clear-cut, one left in its natural condition, one cut under the shelterwood plan, and one cut selectively, found that seedlings became established in greatest numbers on the shelterwood plot. Height growth of Douglas fir and Engelmann spruce seedlings, also, was best on the shelterwood plot. A count made at the end of a 10-year study showed that the number of seedlings per acre was nearly the same where slash had been scattered as where it had been piled and burned.

Haig (*7*), working in northern Idaho, conducted a study in the western white pine type similar to the study in the Douglas fir type described here, using western white pine, Douglas fir, and other species. He made observations on a clear-cut area, on a selectively cut area, and under virgin timber. The light value on the clear-cut area (full sunlight) was considered 100 percent; on this basis black and white Livingston cup atmometers showed light values of 26 percent for the selectively cut area and 5 percent under the virgin timber. From May to September (1932) the daily maximum surface-soil temperature averaged 112° F. on the full-sun area, 104° on the selectively cut area, and 73° under the virgin stand; the seasonal maxima for the respective areas were 144°, 131°, and 89°. On the full-sun area daily maximum temperatures were taken on a "natural mineral surface," a prepared "burnt mineral surface," and a prepared "duff surface"; the seasonal average was 112° for the natural mineral surface, 113° for the burnt mineral, and 130° for the duff, and the seasonal maxima for the respective surfaces were 144°, 151°, and 160°. The author stated that temperatures were lower on the burnt mineral surface during spring months because it remained more moist. In August, when the soils had dried out, the average daily maximum was 125° for the natural mineral, 132° for the burnt mineral, and 138° for the duff surface, and the monthly maxima for the respective surfaces were 144°, 151°, and 156°. (The first two of these temperatures are similar to temperatures recorded on comparable surfaces in the Douglas fir region, where a summer drought period is the rule.) During 1932, fungi, insects, and birds killed 18 percent of the Douglas fir seedlings; of the remainder heat, drought, and other agents killed 83 percent in full sunlight, 21 percent in part shade, and 17 percent in full shade. Haig assumed that 120° is the surface temperature at which seedling injury begins. He stated that insolation losses in 1932 were in general greater on the duff surface than on the mineral surfaces. He concluded that blackening of the mineral surface did not greatly increase seedling losses.

Burning was found by Isaac,[4] in the Pacific Northwest, to alter site conditions markedly. Temperatures on a black, charred soil surface were found to be higher by 7° to 18° F. than those on a yellow soil surface. This temperature difference accounted, in one instance, for the difference between a 100-percent loss of Douglas fir seedlings on a black soil surface and a 32-percent loss on an adjoining yellow soil surface. Injury began at a surface-soil temperature of 125° (which may occur at an air temperature of 85°) or at higher temperatures, according to the age of the seedlings. Indications were found that the blackening of the surface by burning may in itself cause the loss of most of a year's Douglas fir seedling crop. The highest surface-soil temperature recorded for yellow soil was 147°, and the highest recorded for black soil was 165°.

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[4] ISAAC, L. A. SEEDLING SURVIVAL ON BURNED AND UNBURNED SURFACES. Pacific Northwest Fores Expt. Sta., Forest Research Notes No. 3: 3–4, 1929. [Mimeographed.]

Isaac (*10*) found that great variations may occur in distance of seed dissemination, owing principally to variability of air movement. These may result in uneven stocking, which might wrongly be charged to some other site factor. In his experiments (*11*) very little Douglas fir seed was found to remain viable after the first year. Direct evidence was found that seed stored in the soil or duff germinates profusely the first season after it falls, both under old-growth timber and in the open. Seedlings under timber [5] died shortly after germinating, probably from inadequacy of light and moisture.

## DESCRIPTION OF STUDY AREAS AND SAMPLE PLOTS

Three adjoining areas were selected for study on a broad flat in the upper Wind River Valley. These areas are very similar in elevation, aspect, and soil. The elevation, which is practically uniform, is about 1,500 feet. The soil is a loose yellow shot loam, common in the Douglas fir region. It is underlain by lava rock that occasionally appears at the surface, and contains a varying quantity of fine broken rock. According to the accepted site-quality classification of Douglas fir lands, these areas are a good site III.

Formerly, the three areas were very similar as to cover. The old-growth timber of the flat, which now remains on one of the study areas but has been removed from the others, is Douglas fir with a light mixture of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* D. Don), western white pine (*Pinus monticola* D. Don), silver fir (*Abies amabilis* (Loud.) Forbes), noble fir (*A. nobilis* Lind.), and lowland white fir (*A. grandis* Lind.). The principal secondary tree species and shrubby and herbaceous species occurring under the old-growth timber, listed approximately in order of importance, are vine maple (*Acer circinatum* Pursh), Pacific dogwood (*Cornus nuttallii* Aud.), salal (*Gaultheria shallon*), Oregon hollygrape (*Odostemon* spp.), huckleberry (*Vaccinium* spp.), sword fern (*Polystichum munitum*), vanilla leaf (*Achlys triphylla*), wood sorrel (*Oxalis* spp)., starflower (*Trientalis latifolia*), and Pacific trillium (*Trillium ovatum*). On the logged and slash-burned areas the original ground-cover species persisted after logging and fire, but the herbaceous species were for the most part crowded out during the study period by invading species. The most important of the latter are bracken (*Pteridium aquilinum*), fireweed (*Epilobium angustifolium*), blackberry (*Rubus ursinus*), groundsel (*Senecio vulgaris*), and pearl everlasting (*Anaphalis margaritacea*).

On area A the timber was clear-cut and logged by the standard high-lead method in 1924 and 1925, and the the slash was burned in August 1925. The fire was so hot that it consumed all the finer debris and most of the surface humus, leaving the soil bare or with a light coating of charcoal. It burned the shrub growth so severely that in the fall of 1926 the area was practically without plant cover. Conditions on this area (fig. 1) are a good example of those resulting from a severe slash fire.

On area B the timber was clear-cut and logged by the same method in 1919 and the slash was burned in the spring of 1920. This fire was less intense than that on area A, and left considerable debris and charred duff on the soil surface. A brush and herbaceous cover developed quickly, forming a moderately heavy shade by the time the plots were laid out. On this area (fig. 2) are typified the less severe ground conditions resulting from a light slash fire. On both areas A and B cover density increased yearly during the first 5 years of the study, but the increase was slower on the heavily burned area than on the lightly burned area.

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[5] ISAAC, L. A. DESTINY OF DOUGLAS FIR SEEDS THAT FALL IN THE VIRGIN FOREST. Pacific Northwest Forest Expt. Sta., Forest Research Notes No. 5: 4-5. 1931. [Mimeographed.]

On area C (fig. 3), a 1,000-foot strip separating areas A and B, the old-growth stand has not been disturbed and is moderately and uniformly dense. The area has a fairly uniform surface layer of fine litter and duff from 1 to 1½ inches deep.

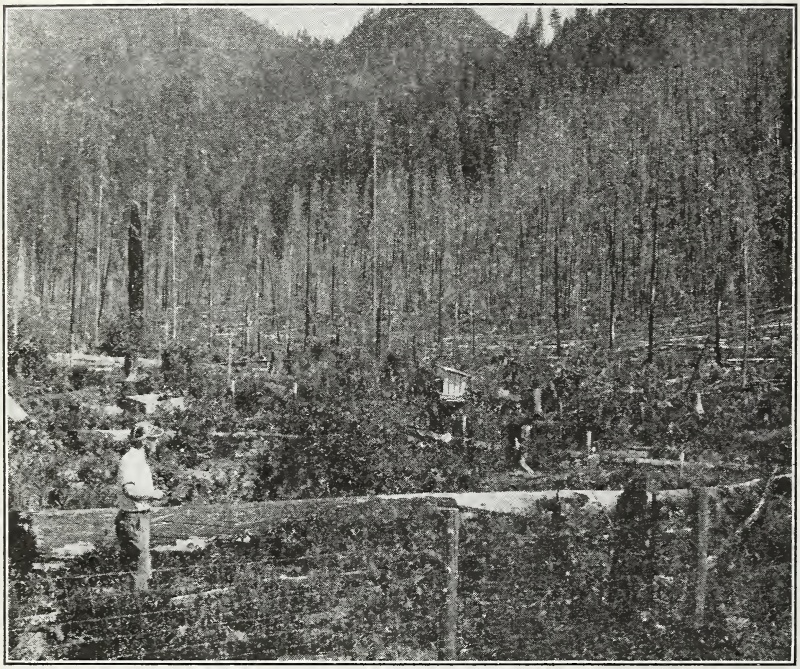

FIGURE 1.—Plots on area A. This area was clear-cut in 1924–25 and heavily slash-burned in August 1925. Cover conditions in 1932, shown here, were typical for Douglas fir lands clear-cut and severely burned.

In site quality, in cover conditions, and in other conditions affecting seedling establishment, the study areas are approximately typical of the greater part of the forest land of the Douglas fir region.

On each of the three permanent study areas three sample plots were established. Each plot was 6.6 feet wide and 132 feet long. The three plots on each area were laid out parallel to each other, with 6-foot spaces between them, and all plots were divided into 6.6-foot (1 mil-acre) segments. The three series of plots are within one-half mile of each other.

Three areas adjacent to study area A were used temporarily in 1931 for measurement of the influence of exposure and slope on physical factors studied. These areas resembled area A as to ground conditions, but were 500 feet higher. Their exposures were south, east, and west, respectively.

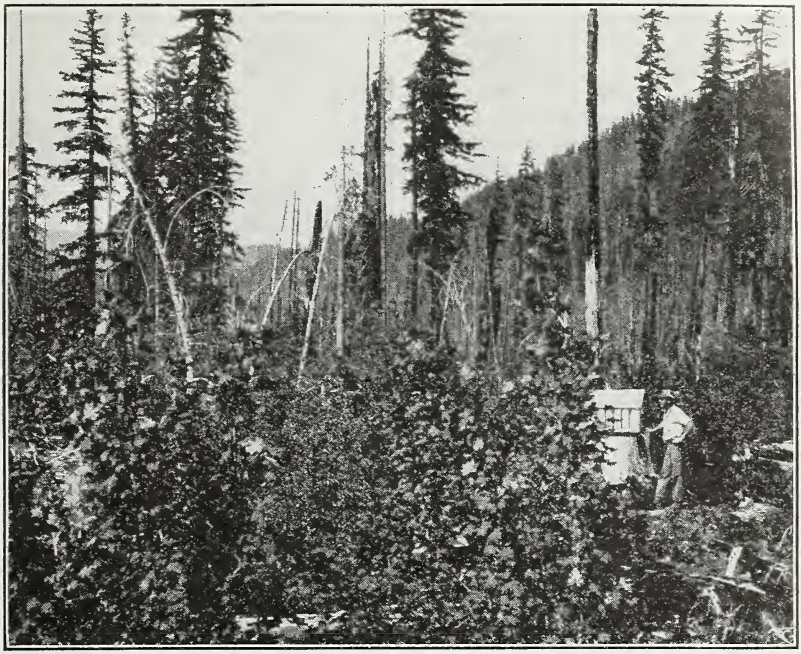

FIGURE 2.—Plots on area B. This area was clear-cut in 1919 and lightly burned in the spring of 1920. The photograph, taken in August 1932, shows the moderately heavy brush cover that typically develops in 12 years on areas clear-cut and lightly slash-burned.

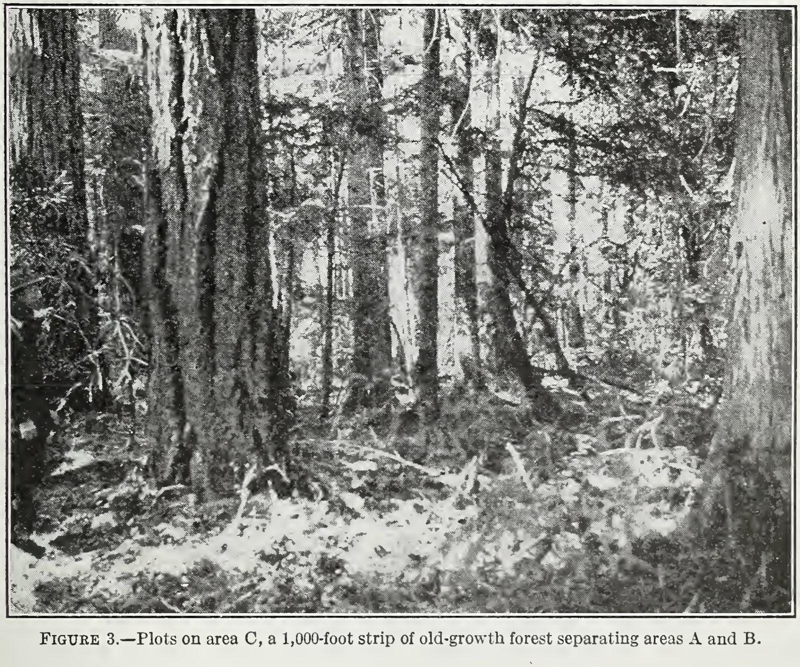

FIGURE 3.—Plots on area C, a 1,000-foot strip of old-growth forest separating areas A and B.

## ENVIRONMENTAL FACTORS, METHODS OF MEASURING THEM, AND RESULTS OF MEASUREMENTS

The interrelated environmental factors studied were air and soil temperatures, evaporation and solar radiant energy, soil moisture, and precipitation. Observations were made also on the effects of shade, plant competition, exposure, slash burning, and attack by biologic enemies.

Each year, observations were started with the beginning of germination in the spring and ended with the first heavy fall rains. Meteorological records were made daily in 1927 and 1928 and until July 1 in 1929, and weekly thereafter. Such records were made regularly in the morning; over short periods, some additional records were made at regular intervals during the day. During 1927, observations were interrupted by prolonged forest fires and unfavorable weather conditions; therefore only part of the 1927 records were used.

### TEMPERATURE

Temperatures, particularly surface-soil temperatures, are of great significance in Douglas fir seedling establishment. Immediately after germination, which commonly occurs within the period from late April to late June, the seedlings are highly susceptible of injury by heat at the soil surface. Surface-soil temperature is governed primarily by air temperature, but is influenced by shade, exposure, soil moisture, and soil color. Seedlings are susceptible also to frost, which affects them either directly or through heaving of the soil. Therefore the study of environmental factors included maximum and minimum air temperatures, and maximum and minimum soil temperatures at the surface and at specified depths.

#### MAXIMUM AIR TEMPERATURES

Air temperatures were taken, in degrees Fahrenheit, with maximum-minimum thermometers of the Sixe type at a height of 5 feet from the ground. The thermometer on area A was housed in an orchard-type instrument shelter, open on the north side; that on area B was suspended in a well-shaded position in the center of a large bush; and that on area C was hung on the north side of a large tree.

The differences among the maximum air temperatures on areas A, B, and C, respectively, remained fairly constant during the period of the study. Typical of these relations and also of the seasonal trend of maximum air temperatures is the 1931 record of weekly maxima on the three areas, shown in figure 4. The maxima on area B were sometimes a little above and sometimes a little below those on area A (where the brush cover was much lighter), but the differences were never great. For the 4-year period 1928–31, the maxima on area C (under old-growth timber) averaged about 8° F., or 9 percent, lower than those on area A.

The highest air temperature recorded on the three areas during the 5 years 1927–31 was 112° F., which occurred on July 25, 1928, on area A. The lowest daily maximum air temperature recorded in the growing seasons of those years was 52°, which occurred on May 26, 1929, on area A.

The maximum air temperatures recorded at the Wind River Experimental Forest headquarters, 10 miles down the valley from the study areas, in each of the spring and summer months during the

21-year period 1911–31 are shown in table 1. Those for the years of the study are a few degrees higher than the corresponding temperatures recorded on the timbered study area C and a few degrees lower than the corresponding temperatures recorded on area A. The 21-year record reveals that the monthly maximum air temperatures recorded on the study areas in the 4 years 1928–31 were by no means abnormal for the vicinity. It reveals also that in this vicinity air temperatures approximating 90° F. do not occur in some years until July, but that in an occasional year an air temperature of 85° or more occurs before the first of May.

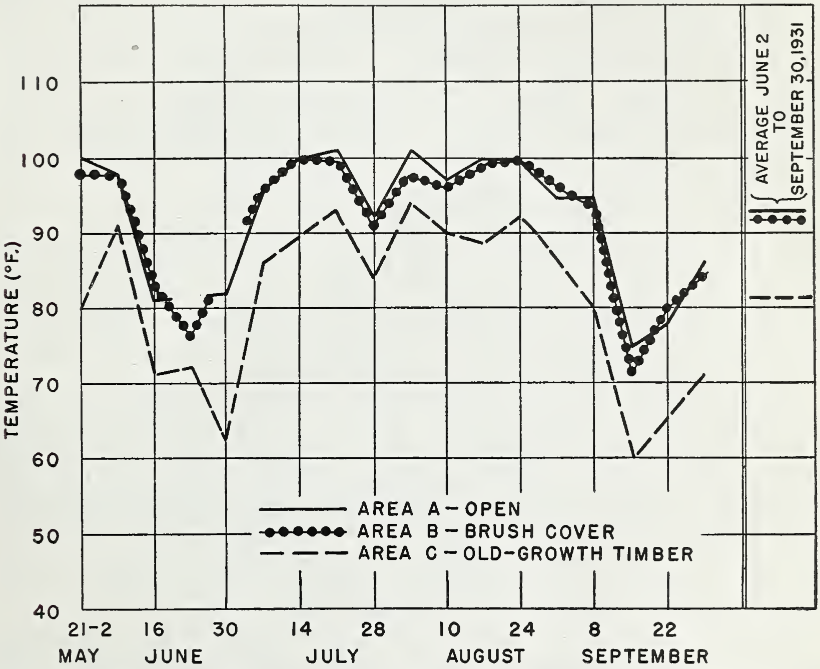

FIGURE 4.—Weekly maximum air temperatures recorded on areas A (open), B (brush-covered), and C (old growth timber) during the growing season of 1931.

TABLE 1.—*Monthly maximum air temperatures recorded for the months of April to September during the 21-year period 1911–31 at Wind River Experimental Forest,*[1] *Carson, Wash.*

| Year | Apr. | May | June | July | Aug. | Sept. |
|---|---|---|---|---|---|---|
| | *°F.* | *°F.* | *°F.* | *°F.* | *°F.* | *°F.* |
| 1911 | 75 | 87 | 89 | 101 | 90 | 84 |
| 1912 | 72 | 87 | 90 | 95 | 98 | 85 |
| 1913 | 73 | 88 | 93 | 98 | 97 | 87 |
| 1914 | 79 | 90 | 92 | 96 | 99 | 85 |
| 1915 | 78 | 78 | 100 | 95 | 102 | 88 |
| 1916 | 70 | 80 | 95 | 90 | 100 | 90 |
| 1917 | 62 | 76 | 88 | 100 | 95 | 87 |
| 1918 | 81 | 79 | 90 | 91 | 95 | 89 |
| 1919 | 74 | 85 | 85 | 96 | 92 | 83 |
| 1920 | 76 | 84 | 88 | 91 | 99 | 82 |
| 1921 | 67 | 82 | 86 | 90 | 98 | 76 |
| 1922 | 69 | 90 | 96 | 102 | 92 | 90 |
| 1923 | 79 | 84 | 94 | 89 | 96 | 90 |
| 1924 | 79 | 93 | 92 | 95 | 94 | 96 |
| 1925 | 80 | 85 | 100 | 93 | 94 | 92 |
| 1926 | 92 | 82 | 99 | 103 | 94 | 88 |
| 1927 | 79 | 85 | 94 | 102 | 94 | 83 |
| 1928 | 73 | 92 | 92 | 101 | 94 | 93 |
| 1929 | 74 | 85 | 88 | 96 | 99 | 92 |
| 1930 | 75 | 80 | 89 | 97 | 98 | 93 |
| 1931 | 85 | 94 | 96 | 96 | 97 | 91 |

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[1] The weather station at which the data were recorded, which is maintained in cooperation with the Weather Bureau, is at the forest headquarters, 10 miles down the valley from the study areas.

## MAXIMUM SURFACE-SOIL TEMPERATURES

Injury to seedlings from heat or cold usually occurs at the point where the seedling stem emerges from the ground; therefore surface-soil temperatures are of utmost importance in this study. (The term "surface-soil temperature" as used in this report means the temperature of the upper one-eighth inch of surface soil.) These temperatures were taken with the gooseneck type of registering thermometer.[6] This thermometer, which has a range of +20° to +180° F., is about 10 inches long and one-eighth inch in diameter, and has an offset of about one-eighth inch in the stem just above the mercury bulb. When the thermometer is set the bulb is imbedded in the surface soil and completely covered with a thin layer of it, and the stem lies flat on top of the soil.[7] Maximum surface-soil temperatures recorded for all the areas in the years 1928–31 are shown in figure 5, together with the air temperatures recorded concurrently in the weather shelter on area A. In the following discussion, the seasonal averages quoted represent annual periods somewhat longer than those for which data are shown in figure 5.

Surface-soil temperatures on area A were measured on a natural gray soil surface completely exposed to the sun except for a light weed shade in early morning and late afternoon. Their weekly mean maxima for 1928 averaged 40.9° F. (50 percent) higher than the weekly mean maxima of concurrent air temperatures. Their weekly maxima for 1929, 1930, and 1931 averaged 44.4° (49 percent) higher than the corresponding air-temperature maxima.

On area B, in 1928 the weekly mean maxima of surface-soil temperatures, taken in the shade of a 6-foot dogwood bush, averaged 7.8° F. (9.1 percent) higher than those of air temperatures; in 1929, 1930, and 1931 the weekly maxima of surface-soil temperatures averaged 26.6° (29.1 percent) higher than those of air temperatures. Soil temperatures on area B, while considerably below those on area A, often rose high enough to cause injury to seedlings. They did this only when shafts of direct sunlight through the leaf canopy struck the thermometer bulb for a short time.

Under the timber, on area C, the temperatures of the surface soil ran close to those of the air; their weekly mean maxima for 1928 averaged only about 5° F. (6 percent) lower, and their weekly maxima for 1929, 1930, and 1931 averaged 1° (1 percent) higher, than those of the concurrent air temperatures. During the early part of each growing season, surface temperature usually remained below air temperature; in June and July, when the sun's rays were most nearly vertical, it rose above air temperature; and later in the season it dropped below it. At no time did the surface-soil temperature under the timber rise high enough to cause injury to seedlings.

The highest surface-soil temperature recorded on normal gray soil was one of 164° F. in 1930, which was developed on the open area on July 15, at an air temperature of 102°.

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[6] Much difficulty and much breakage in shaking down the mercury columns were eliminated by designing a special shaker. The shaker operates like a sling psychrometer; the thermometer is clamped into it and is whirled until the mercury is driven down.

[7] Surface-soil temperatures were taken with the stem of the thermometer fully exposed. Tests were made to determine whether direct sunlight on the stem affected temperatures. It appeared to make no appreciable difference in the readings.

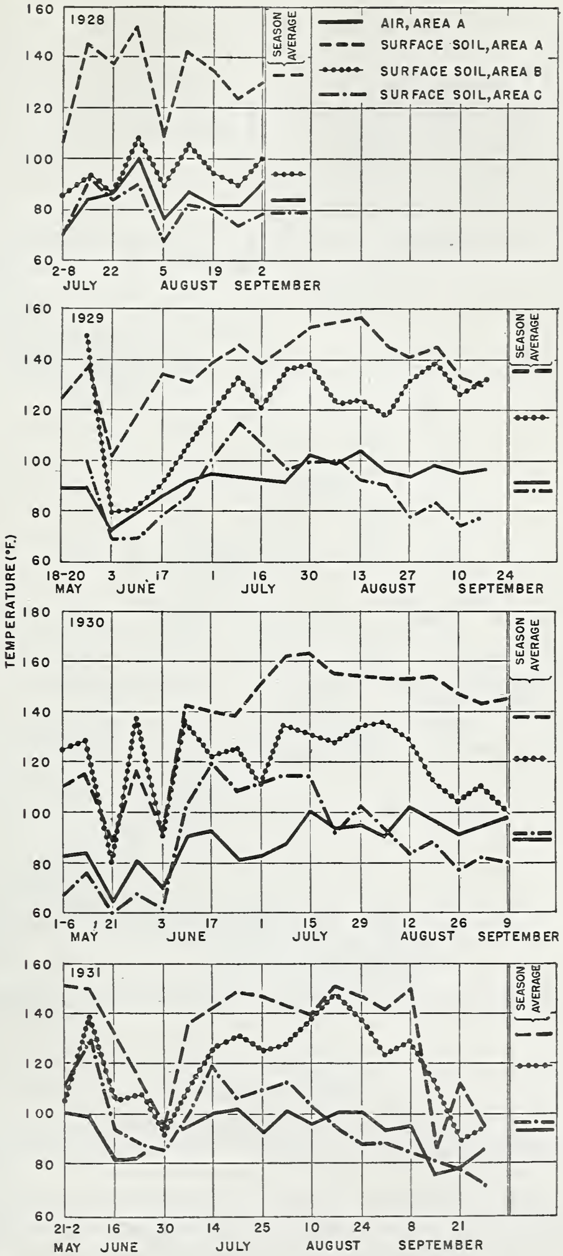

FIGURE 5.—Weekly maxima air and surface-soil temperatures recorded on areas A (in the open), B (in shade of dogwood bush), and C (in shade of old-growth timber) in the growing seasons of the 4-year period 1928–31. "Surface-soil temperature" here means temperature of upper one-eighth inch of surface soil. In a few instances, the data shown represent periods slightly more or less than a week. None of these graphs shows the whole of an annual record; in each case, some data taken early and late in the season are omitted.

### RELATION TO MAXIMUM AIR TEMPERATURES

The graph of weekly mean maximum air and surface-soil temperatures for 1928 shows for each of the three areas the general seasonal trend of surface-soil temperature in relation to air temperature. The surface-soil temperature developed at a given air temperature varies with other atmospheric conditions and with soil and cover conditions. Daily maximum surface-soil temperatures recorded concurrently with given daily maximum air temperatures on the study areas in 1927, 1928, and early 1929 are shown in figures 6 and 7. In preparing these figures air temperatures were averaged by 10-degree groups and the surface-soil temperatures recorded concurrently with these air temperatures were averaged. (A similar procedure was followed in preparing figs. 8, 9, 13, and 14.)

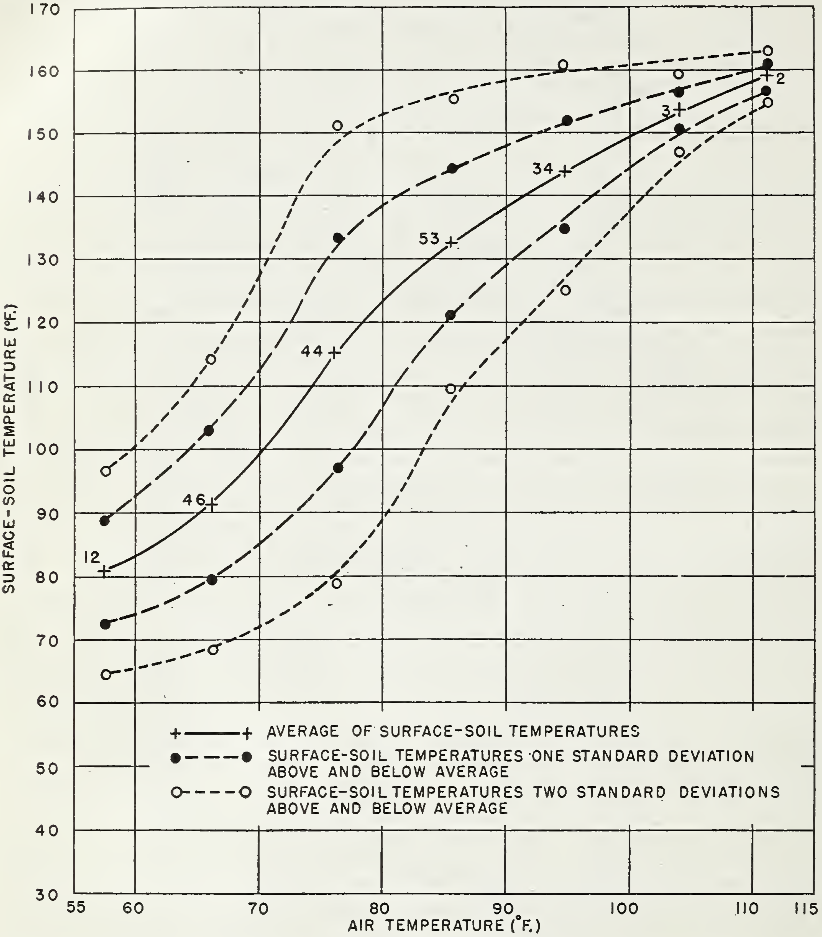

FIGURE 6.—Range of daily maximum surface-soil temperatures recorded concurrently with given daily maximum air temperatures on gray mineral soil without shade, on area A, in 1927, 1928, and 1929. (Figures indicate number of observations.)

On area A, as is shown in figure 6, the difference between air and surface-soil temperature maxima in general gradually increased as air-temperature maxima increased. At a maximum air temperature of 57° F., the spread was 23°; at a maximum air temperature of 111°, it was 48°. The increase in spread was not always proportional to the increase in maximum air temperature. The range of maximum temperatures that may be expected in unshaded gray mineral surface soil at any given maximum air temperature is shown in figure 6 by the curves of one and two standard deviations; of the surface-soil temperatures developed at an air temperature of 90°, for example, 67 percent fell between 128° and 148° and 95 percent fell between 118° and 158°. The standard deviations are greatest near the center of the temperature range and least at the extremes.

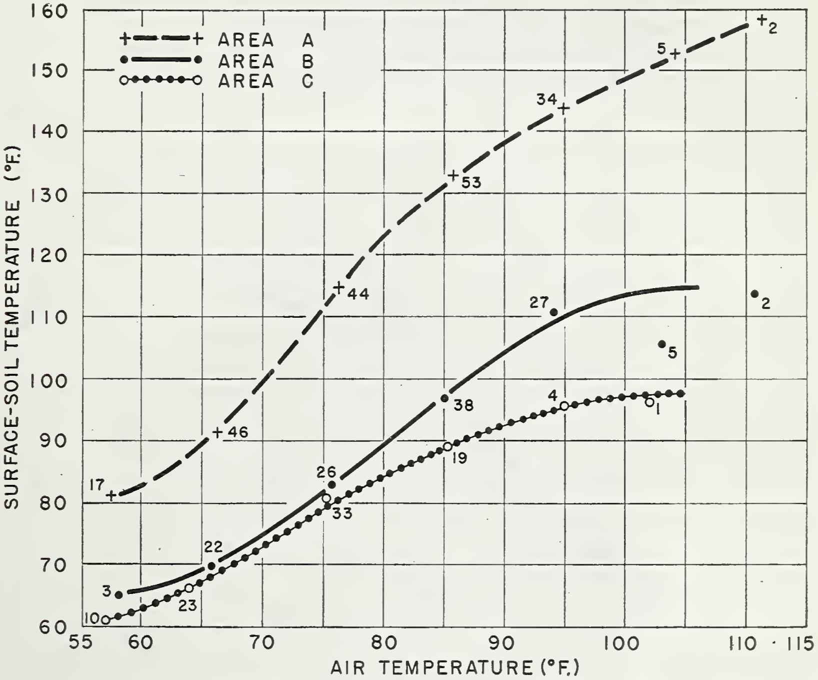

FIGURE 7.—Average daily maximum surface-soil temperatures recorded concurrently with given daily maximum air temperatures on study areas A (in the open), B (in shade of dogwood bush), and C (in shade of old-growth timber) in 1927, 1928, and 1929. (Figures indicate number of observations.)

Figure 7, in which data of the seasons 1927, 1928, and 1929 are combined for each of the three areas as was done in figure 6 for area A only, brings out the influence of cover on surface-soil temperature in a more concise manner than figure 5. At the lower air temperatures, surface-soil temperatures on the brush-covered area differed little from those on the old-growth timber area. The former were slightly higher, the spread increasing as air temperature increased. The spread between the surface temperature on the open area and that on the old-growth timber area began with 20° F. when the air temperature was 60° and increased to 50° when the air temperature was 100°.

### INFLUENCE OF SOIL COLOR AND OF SHADE

Color of surface soil had a pronounced effect on maximum surface-soil temperature. This is shown by figure 8, which represents daily readings made on the open area during 1928 and 1929 in a light-yellow mineral surface soil, a natural-gray mineral surface soil, and a surface soil blackened by charcoal. The temperature of the yellow soil was invariably the lowest. That of the gray soil was higher by an average of about 5° F. That of the black soil was about the same as that of the gray soil at the lower air temperatures, but at higher air temperatures the black soil heated more rapidly than the others until at 100° air temperature it reached a temperature of 163°, 15° above that of the gray soil and 19° above that of the yellow soil. This difference in temperature between a blackened soil surface and natural-colored soil surfaces has a significant bearing on seedling establishment, as is shown later.

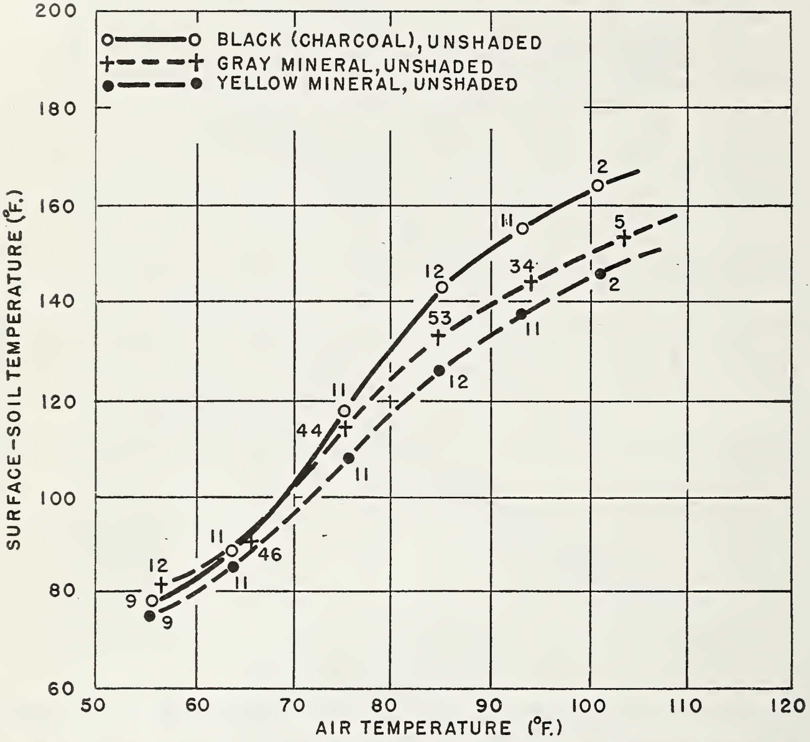

FIGURE 8.—Average daily maximum temperatures recorded in different-colored unshaded surface soils on area A, in 1928 and 1929, concurrently with given daily maximum air temperatures. (Figures indicate number of observations.)

The most severe weather experienced during the study was that of the period July 24–28, 1928. On July 24 the air temperature rose to 111° F. and the temperature on a charcoal-blackened surface rose to 166°. For the 5-day period the daily maximum temperature of the air averaged 103°, that of the yellow surface soil 144°, and that of the black surface soil 156°. Additional surface temperatures were taken in the shade of fireweed, a dogwood bush, and a stump 30 inches in diameter and 4 feet high. These and other similar records were combined and averaged in 10-degree air-temperature groups and figure 9 constructed from the points so obtained. The curves show definitely the relation between surface temperatures of fully exposed mineral soils and of mineral soils having shade conditions different from those on areas supporting heavy brush and old-growth timber, represented in figure 7. The temperature of the black soil averaged about 10° above that of the yellow soil in this case. The temperature on a gray surface in the light shade of fireweed averaged a few degrees above the air temperature, and that in the medium shade cast by a small dogwood bush averaged a few degrees below the air temperature. The lowest temperature recorded occurred in the full shade cast by the stump.

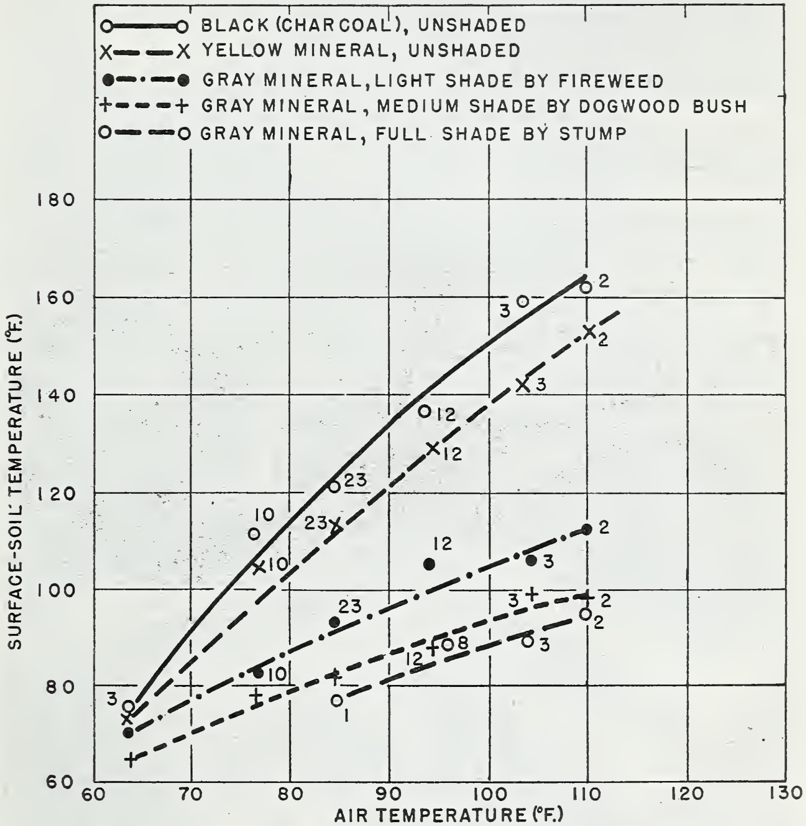

FIGURE 9.—Average maximum surface temperatures of black and yellow unshaded soil, and of gray soil under different conditions as to shade, recorded concurrently with given maximum air temperatures on area A. Records taken at 3-hour intervals during the day. Figures indicate number of observations.

## SOIL TEMPERATURES AT DEPTHS OF 3, 6, AND 12 INCHES

It is possible that subsurface soil temperature affects seedling establishment, through its effect on soil moisture. Soil temperatures at depths of 3, 6, and 12 inches were measured in the four seasons 1928–31, with standard Weather Bureau maximum and minimum thermometers inserted through the end walls of a soil well (fig. 10).[8] The soil well was 2 feet wide, 2 feet deep, and 4 feet long, and was fitted with double covers. At the 3-, 6-, and 12-inch depths, holes 2 inches in diameter were bored through the end wall and out into the soil for a distance of 24 inches. Plug mounts (fig. 10) were made for the maximum and minimum thermometers, and the thermometers were inserted into the holes in the end wall so that the bulbs came into contact with the soil 2 feet out from the wall.

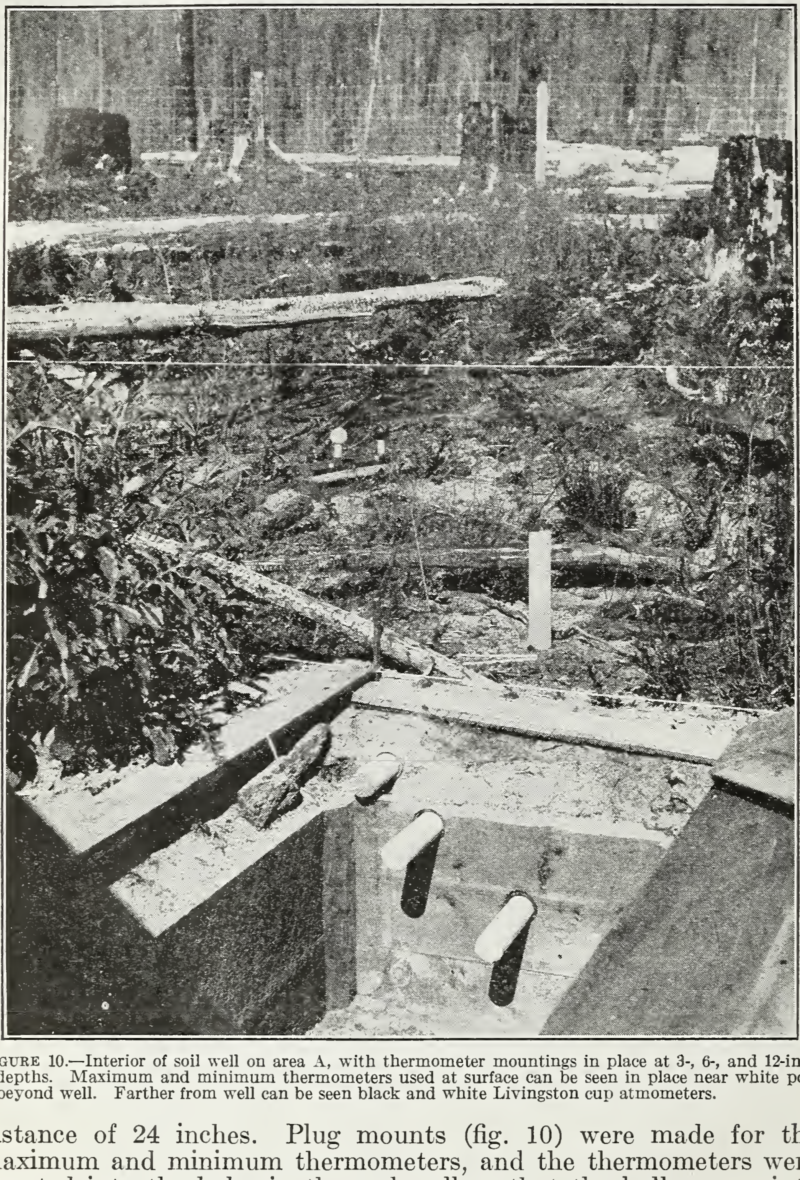

FIGURE 10.—Interior of soil well on area A, with thermometer mountings in place at 3-, 6-, and 12-inch depths. Maximum and minimum thermometers used at surface can be seen in place near white post beyond well. Farther from well can be seen black and white Livingston cup atmometers.

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[8] When air temperature was higher than soil temperature, in setting the standard Weather Bureau maximum thermometers difficulty was experienced in getting the mercury down. To overcome this, the mercury bulb was dipped in alcohol and then exposed to the air. The evaporation of the alcohol reduced the temperature of the mercury below that of the soil.

During part of 1931 a Sixe-type maximum-minimum thermometer was used for measuring subsurface soil temperature on area C. This instrument is incased in a glass shell, like a dairy thermometer. Its sensitive bulb, instead of being close to the body of the instrument, is at the end of a slender 10-inch stem, which is inserted into the soil.

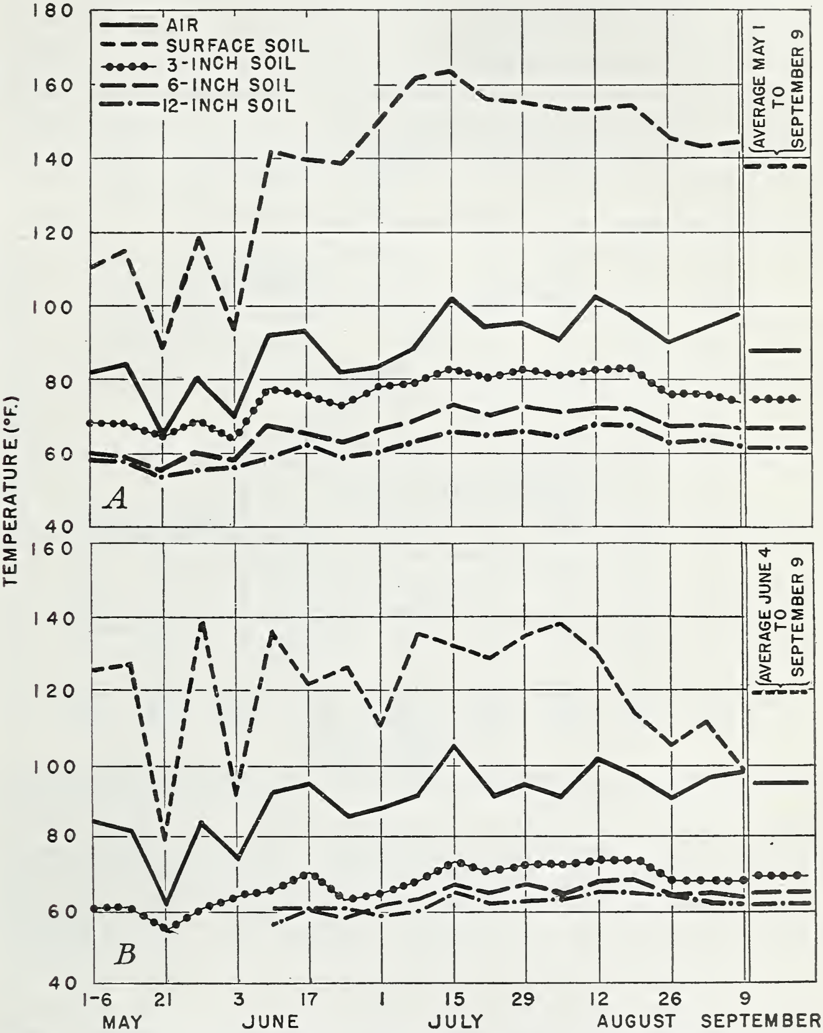

FIGURE 11.—Weekly maximum soil temperatures at depths of 3, 6, and 12 inches and weekly maximum air temperatures in 1930: *A*, area A (open); *B*, area B (brush-covered).

This thermometer could be operated in a smaller soil well and could be read much more conveniently and quickly than the standard Weather Bureau maximum and minimum thermometers. Because it is read and reset in place, no error is introduced in resetting as is sometimes the case with the standard instruments; and for this reason the data obtained with it were as accurate as those obtained with standard instruments, even though it is not quite so accurate as they under laboratory conditions.

Soil temperatures at the 3-, 6-, and 12-inch depths were recorded for areas A and B throughout the growing seasons of the study period. Weekly maxima in 1930, indicative of the seasonal trend, are shown in figure 11. Both the weekly mean maximum soil temperatures for 1928 and the weekly maximum soil temperatures for 1929, 1930, and 1931, at all depths, were higher on area A than on area B. These differences were not great, however; area A was warmer by an average of approximately 9° F. at the 3-inch depth, 2.5° at the 6-inch depth, and 2° at the 12-inch depth. Thus, as may be seen in figure 11, on area B the soil temperatures at different depths were closer to each other and farther from the temperature of the air than they were on area A. Fluctuation of soil temperature with air temperature was more pronounced on area A, where the cover was lighter.

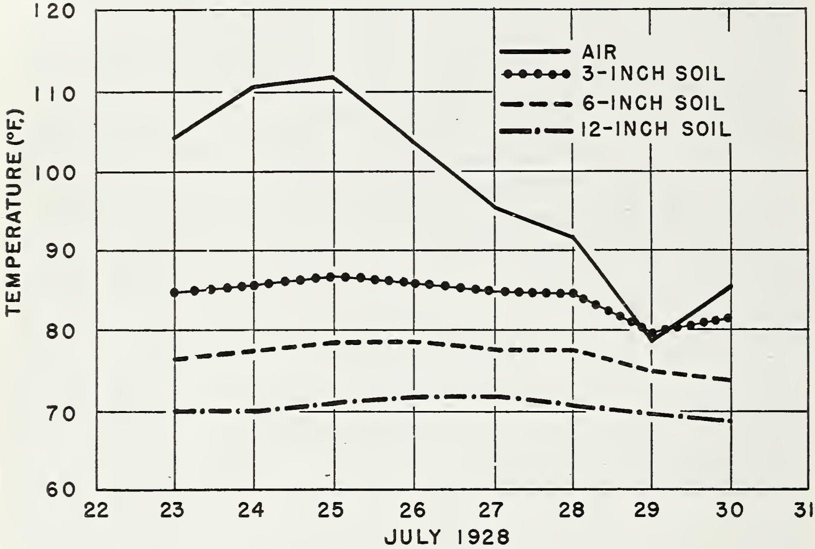

Figure 12.—Daily maximum air and soil temperatures on area A (open) during the period July 23–30, 1928.

Soil temperatures at the 3-inch and 12-inch depths on area C were taken during a period of 4 weeks in September 1931. The daily maximum temperature on area C then averaged 56° F. at the 3-inch depth and 50° at the 12-inch depth, whereas during the same period the average daily maximum on area A was 70° at the 3-inch and 60° at the 12-inch depth, and the average daily maximum on area B at each depth was about midway between those of areas A and C.

The close relationship of the fluctuations of soil temperatures at the 3-, 6-, and 12-inch depths with each other and with the fluctuations of air temperature may be seen in figure 12. With increase in depth, change in temperature is diminished, delayed, and spread over a longer period. Thus subsurface soil temperatures are affected more by the duration of a given high or low air temperature than by extremes of air temperature momentarily attained.

The degree to which maximum air temperatures are reflected in concurrent soil temperatures, and the soil temperatures that may be expected to accompany given maximum air temperatures in this or a similar locality, are indicated in figure 13. A very interesting difference is revealed between the soil temperatures occurring on the two areas at a given air temperature; on area A as compared with area B not only was there a wider spread between temperatures at different depths but temperatures at all depths were much higher, the temperature at the 12-inch depth in the open being very nearly equal to that at the 3-inch depth in brush shade.

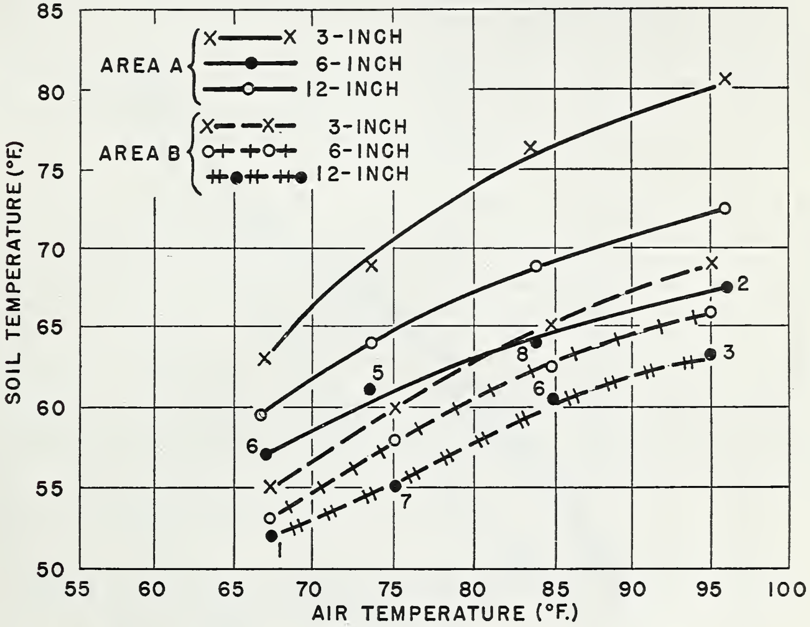

FIGURE 13.—Weekly mean maximum soil temperatures recorded concurrently with given weekly mean maximum air temperatures on area A (open) and area B (brush-covered) in 1928 and 1929. (Figures indicate number of observations.)

Soil moisture is known to influence soil temperature in this locality in the spring and fall, when the moisture content is high; but during the usual summer drought period the soil-moisture content in the Douglas fir region is so low and changes so slowly that it has little or no effect on soil temperature.

### MINIMUM TEMPERATURES

Hot days and cool nights are characteristic of the summer climate of the locality in which this study was made, a 1-day change of 40° F. in air temperature and 100° in surface-soil temperature being not at all uncommon. The greatest 1-day change recorded during the study occurred on July 23, 1928, when within a period of 24 hours air temperature fell from 105° to 56° and surface-soil temperature from 158° to 42°—a drop of 49° in air temperature and 116° in surface-soil temperature.

Daily or weekly minimum air and soil temperatures were recorded regularly, from 1927 to 1931. Significant differences were found between minimum air and surface temperatures in the open and those under timber and brush cover. Between May 6 and May 14, 1930, air temperature dropped to 27° and 26° F. on several nights. During this time minimum surface-soil temperatures as low as 23° were recorded on exposed spots on area A. On that area minimum surface-soil temperature averaged several degrees lower than minimum air temperature, and only in a few instances equaled or exceeded it.

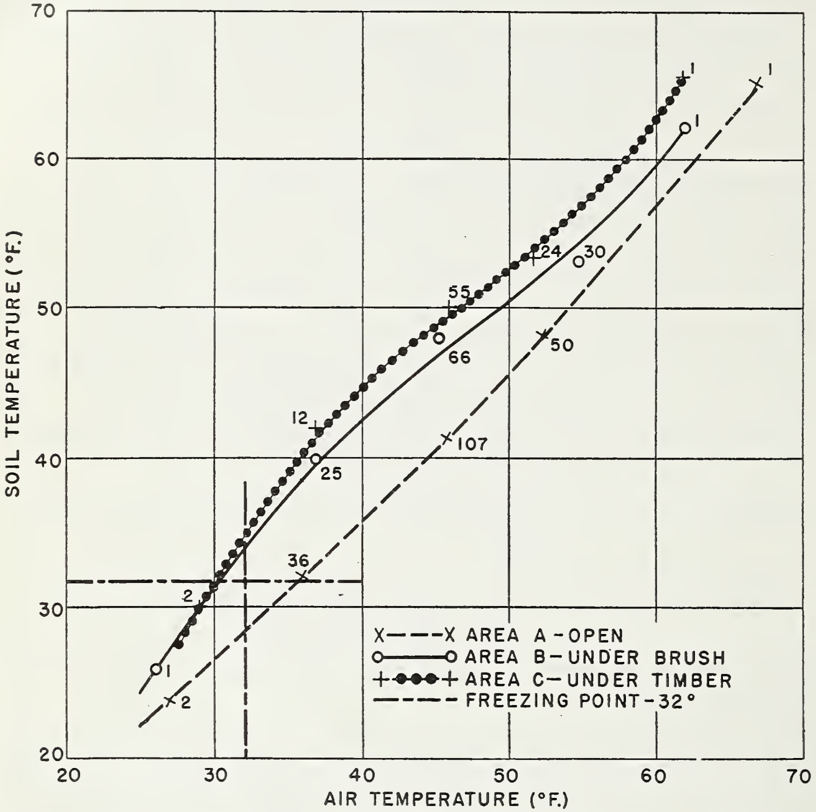

FIGURE 14.—Average daily minimum air temperatures and corresponding average daily minimum surface-soil temperatures recorded in 1927–29 on study areas A (in the open), B (in shade of dogwood bush), and C (in shade of old-growth timber). (Figures indicate number of observations.)

The greatest difference between concurrent minimum temperatures of the air and the surface soil recorded during the study was 14°, shown by area A records for July 23, 1928. On area B the minimum surface-soil temperature shown for that day, by a thermometer under a dogwood bush, just equaled the minimum air temperature, indicating the influence of cover. In average weather, under brush cover minimum surface-soil temperatures averaged several degrees above minimum air temperatures and on bare ground they averaged as many degrees below; they remained consistently above or below, according to cover conditions.

Analysis of data on minimum subsurface soil temperatures led to no significant findings.

Average daily minimum air and surface-soil temperatures are shown in figure 14. Air and surface soil differed much less in minimum temperatures than in maximum temperatures; the average of standard deviations was 2.8° F., and the greatest standard deviation was 4.6°. The curves definitely show that minimum surface temperature was influenced by cover throughout its range. When the air temperature in the weather shelters was at freezing (32°), the curves indicate the surface temperature in the open was 4° lower, that in the shade of a dogwood bush was 2° higher, and that under old-growth timber was 3° higher. On fully exposed surfaces, freezing temperatures may occur when air temperatures are in the neighborhood of 36°; on surfaces under old-growth timber or brush they are not likely to occur until air temperatures get down to 30° or 31°.

## PRECIPITATION

Rainfall (or the lack of it) during the growing season, because of its effect on soil temperature and soil moisture, is of importance among the environmental factors that govern seedling establishment. A summary of rainfall during spring and summer months of the 21-year period 1911–31 at Wind River Experimental Forest headquarters is shown in table 2. The annual total at this point during 1911–31 averaged approximately 84 inches. As is characteristic of the Douglas fir region, in most years nearly all the rainfall came in the fall, winter, and spring, a protracted period of drought occurring in the summer. In 10 years out of the 21, July precipitation totaled not more than 0.1 inch; in 8 years out of the 21, August precipitation totaled not more than 0.1 inch; in 7 years out of the 21, July and August precipitation combined totaled less than 0.32 inch.

TABLE 2.—*Precipitation recorded for the months April to September during the 21-year period 1911–31 at Wind River Experimental Forest,*[1] *Carson, Wash.*

| Year | April | May | June | July | August | September |
|---|---|---|---|---|---|---|
| | *Inches* | *Inches* | *Inches* | *Inches* | *Inches* | *Inches* |
| 1911 | 3.53 | 9.87 | 0.50 | 0.01 | 0.30 | 7.87 |
| 1912 | 3.48 | 3.59 | 1.94 | .56 | 5.75 | 1.73 |
| 1913 | 6.01 | 2.68 | 4.60 | .82 | .88 | 7.36 |
| 1914 | 6.72 | 2.55 | 3.07 | .23 | (2) | 7.80 |
| 1915 | 5.48 | 5.82 | .24 | 1.25 | .06 | .34 |
| 1916 | 6.27 | 5.84 | 2.83 | 2.57 | .79 | 2.30 |
| 1917 | 10.75 | 2.14 | 2.17 | .16 | .00 | 2.20 |
| 1918 | 2.73 | 3.49 | .02 | .72 | .89 | .72 |
| 1919 | 7.23 | 4.72 | 2.08 | .20 | .08 | 5.08 |
| 1920 | 9.31 | 2.34 | 3.53 | .58 | 2.51 | 10.98 |
| 1921 | 8.41 | 1.90 | 2.84 | .10 | 1.06 | 4.19 |
| 1922 | 5.55 | 2.80 | .14 | .00 | 2.36 | 2.36 |
| 1923 | 4.56 | 3.45 | 1.11 | 1.49 | 1.78 | 1.06 |
| 1924 | 1.63 | .81 | 1.35 | .06 | .88 | 5.52 |
| 1925 | 5.27 | 2.61 | 2.35 | (2) | .49 | 1.49 |
| 1926 | 2.39 | 5.32 | .02 | (2) | 1.98 | 7.47 |
| 1927 | 4.66 | 6.23 | .40 | .01 | .79 | 7.72 |
| 1928 | 10.31 | 1.81 | .78 | .52 | .01 | .72 |
| 1929 | 8.97 | 2.01 | 3.66 | (2) | .05 | .32 |
| 1930 | 5.04 | 5.10 | .85 | (2) | .07 | .96 |
| 1931 | 4.83 | 1.61 | 4.51 | .00 | .06 | 4.15 |
| Average | 5.86 | 3.65 | 1.86 | .44 | .99 | 3.92 |

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[1] The weather station at which the data were recorded, which is maintained in cooperation with the Weather Bureau, is 10 miles down the valley from the study areas.

[2] A trace.

In this study precipitation was measured with the ordinary 10-to-1 rain gage, always at the same hour of the day, and was recorded in hundredths of an inch. No record was made of hour of fall. On area A, records were taken daily in the 1927 and 1928 seasons and until July 1, 1929, and weekly for the remainder of the 1929 season and in the seasons of 1930 and 1931. On areas B and C, rainfall was recorded for short periods for the purpose of comparison with rainfall on area A.

The rainfall recorded on area A, shown in table 3, was similar to that recorded at the experimental forest headquarters for the same periods. The heaviest total for July and August was 0.76 inch. In 1929 only 0.03 inch fell between June 24 and September 2. In 3 of the 5 years no rain fell during July.

While the rainfall for the study period was slightly below the 21-year average for the locality, a comparison of tables 2 and 3 will show that the study years could not be called abnormal in either amount or season of fall.

For June, July, August, and September 1931 (table 4) the gage on area A showed a total rainfall of 6.51 inches, that on area B 4.60 inches, and that on area C 4.85 inches; that is, the gages on B and C showed totals averaging 27 percent less than that on A. These figures indicate that on forested and brush-covered areas a considerable proportion of the rainfall is intercepted by the cover, particularly in the case of light rains.

TABLE 3.—*Rainfall on area A*[1] *in the growing seasons of the 5 years, 1927–31*

| Year | Observation period | May | June | July | August | September |
|---|---|---|---|---|---|---|
| | | *Inches* | *Inches* | *Inches* | *Inches* | *Inches* |
| 1927 | July 1 to Sept. 30 | | | 0 | 0.76 | 7.22 |
| 1928 | June 1 to Sept. 15 | | 0.91 | .66 | .10 | .67 |
| 1929 | May 12 to Sept. 15 | 1.09 | 3.50 | 0 | .03 | .60 |
| 1930 | May 1 to Sept. 30 | 3.92 | .56 | .16 | .07 | .32 |
| 1931 | May 22 to Sept. 30 | | 3.65 | 0 | .04 | 2.82 |
| Average | | 2.50 | 2.16 | .16 | .20 | 2.33 |

[1] Open.

TABLE 4.—*Rainfall on the 3 study areas in the growing season of 1931*

| Day | Area A[1] | Area B[2] | Area C[3] |
|---|---|---|---|
| | *Inches* | *Inches* | *Inches* |
| June 9 | 0.25 | 0.09 | 0.24 |
| June 16 | 1.14 | .96 | 1.02 |
| June 23 | 1.19 | .73 | .71 |
| June 30 | 1.07 | .76 | .87 |
| Aug. 1 | .04 | 0 | 0 |
| Sept. 8 | .43 | .22 | .13 |
| Sept. 14 | .68 | .38 | .37 |
| Sept. 22 | 1.34 | 1.12 | 1.22 |
| Sept. 30 | .37 | .34 | .29 |
| Total | 6.51 | 4.60 | 4.85 |

[1] Open. [2] Brush-covered. [3] Old-growth timber.

## EVAPORATION AND SOLAR RADIANT ENERGY

Evaporation, which reflects the combined effect of temperature, relative humidity, and air movement, has a very significant bearing on seedling establishment. Data on evaporation are especially valuable in this study because no continuous records were taken of air movement and relative humidity. Evaporation was measured by means of Livingston spherical cup atmometers (fig. 10). Rain-correcting valves were placed in the stems, and the reservoirs were set down into the soil to reduce temperature fluctuations in the water. Distilled water was used in the atmometers at all times.

A black-cup atmometer was operated along with the white, continuously on area A and intermittently on areas B and C, in order to measure the difference in evaporation from a black and a white surface and thus determine solar radiant energy (sometimes referred to as light intensity).

On area A the atmometers were exposed to full sunlight (fig. 10); on area B they were shaded by a dogwood bush; and on area C they were shaded by old-growth timber. Evaporation records were taken daily on all three areas in 1928 and until July 1 in 1929, and weekly during the remainder of the growing season of 1929 and in 1930 and 1931. In addition some special records were taken over short periods.

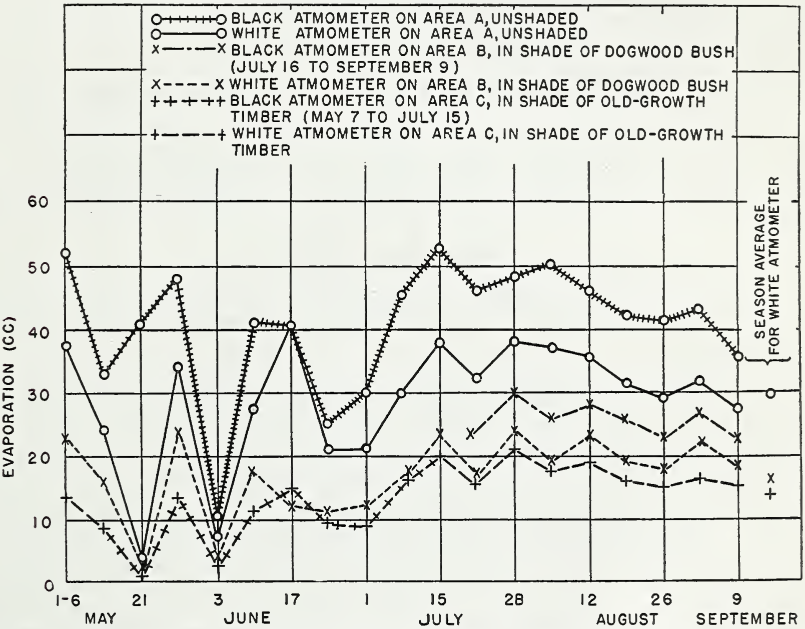

FIGURE 15.—Daily evaporation from black and white atmometers on areas A (in the open), B (in shade of dogwood bush), and C (under old-growth timber) in 1930. The data shown are averages for weeks or, in a few instances, periods slightly more or less than a week. The record of evaporation under old-growth timber obtained with the black atmometer—which covers the period May 7 to July 15 only—and that obtained with the white atmometer differed only by an average of 0.1 cc daily; consequently, the lines representing these two records coincide.

Daily evaporation from the white sphere on area A averaged 27.8 cc. Average daily evaporation on area B was 17.3 cc, or 37.8 percent less, and on area C was 15.1 cc, or 45.7 percent less. Figure 15, presenting data for 1930, shows the seasonal trend of evaporation; this trend was consistent throughout the period of the study. The figures just given very plainly indicate the influence of both high old-growth timber shade and low brush shade on evaporation as measured with white Livingston cup atmometers. Whether or not the decrease in evaporation resulting from the shade of brush or forest cover is equaled by the loss of water through transpiration from the leaves was not determined.

The solar radiant energy on each of the study areas in the season of 1930 is indicated by the curves of evaporation shown in figure 15.

Daily evaporation from the black sphere on area A for the four seasons averaged 40.5 cc, which was 12.7 cc, or 45.7 percent, higher than that from the white. For a period of 8 weeks in late 1930 the black sphere on area B showed an average daily evaporation of 25.4 cc, which was 5.9 cc, or 30.3 percent, above the daily average shown by the white (fig. 15). (The atmometers on area B received some direct sunlight through the leaf canopy.) For 10 weeks in early 1930 the daily evaporation from the black sphere on area C averaged 10.6 cc, which was 0.1 cc, or 0.9 percent, greater than that from the white.

The 45.7 percent difference between the evaporation from the white sphere and that from the black sphere in the open represents full sunlight, or a light value of 100 percent. On that basis the 30.3-percent difference under brush cover represents a light value of 66 percent, and the 0.9-percent difference under old-growth timber represents a light value of 2 percent. The subject of solar radiant energy is dealt with later, in the discussion of the influence of shade on seedling survival.

## SOIL MOISTURE

The summer drought that is characteristic of the Douglas fir region increases the importance of soil moisture as a factor in seedling establishment.

Soil samples were taken weekly, in the morning, on each of the three study areas during the growing seasons of the 4 years 1928–31, at the 3-, 6-, and 12-inch depths—that is, one sample each from the 1½- to 4½-inch, 4½- to 7½-inch, and 10½- to 13½-inch zones, respectively. Each week, the soil pits were opened, their end walls were shaved back far enough to expose a fresh surface, and samples were taken at each depth. The samples were placed in 12-ounce ointment cans, and the cans were sealed with ordinary cup grease until they could be weighed. For preliminary drying of the samples the lids of the cans were left off for a few days. The cans of soil were then placed in an electric oven and dried at a temperature of 220° F. Moisture content was determined by comparing the weights of the soil samples when fresh with their weights after drying. The results for 1930 are shown in figure 16 (pp. 26–27). The data for the three other seasons were similar, except that soil moisture was somewhat lower in 1928.

At no time during the four seasons did the weekly measurements show a moisture content of less than 12 percent,[9] except at the 3-inch depth. There a content of less than 12 percent was shown by some measurements during each of the four seasons on both area A and area B, including all the measurements for a period of 7 consecutive weeks during 1928 on area A. The lowest moisture content recorded was 5 percent; this occurred on September 3, 1928, at the 3-inch depth on area A.

Soil-moisture averages for the three areas are shown in table 5. At the 3-inch depth, moisture content averaged lowest on area A and highest on area C; at the 12-inch depth, it was highest on area A and was nearly the same on area B as on area C; at the 6-inch depth, it averaged very nearly the same on all areas, the range of difference being only 0.6 percent. Averages for the three depths show very little difference among the three areas.

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[9] In special tests to determine wilting coefficient, discussed later, wilting of seedlings was found to occur at moisture contents up to 12 percent of oven-dry weight of soil; therefore 12 percent is here accepted as the critical point.

TABLE 5.—*Average soil moisture content on the three study areas during the growing seasons* [1] *of the 4 years 1928–31*

| Depth (inches) | Area A [2] | Area B [3] | Acrea C [4] | Average |
|---|---|---|---|---|
| | *Percent* | *Percent* | *Percent* | *Percent* |
| 3 | 17.7 | 18.4 | 20.8 | 19.0 |
| 6 | 21.8 | 21.3 | 21.9 | 21.7 |
| 12 | 26.8 | 23.8 | 24.4 | 25.0 |
| Average | 22.1 | 21.2 | 22.4 | 21.9 |

[1] Measurements were made weekly, in the morning, throughout the growing season of each year.
[2] Open.
[3] Brush-covered.
[4] Old-growth timber.

Contrary to findings in other forest regions, on all areas and for each year the moisture content averaged lowest at the 3-inch depth and highest at the 12-inch depth. As is shown in a preceding section, in the locality of the study areas usually little or no rain falls during the seedling growing season; therefore the soil moisture available for seedling growth is mostly water stored in the soil from precipitation occurring previous to that season.

Throughout the period of this study the measurements made regularly in the morning once each week indicated that soil-moisture content decreased steadily during the summer months on all areas at all depths. During one hot, dry period in 1928, soil samples were taken at the 3-, 6-, and 12-inch depths on area A at 3-hour intervals from 8 a. m. to 5 p. m. This sampling yielded evidence that soil moisture was sometimes less, for one or more days within a week, than it was at the time of the next regular weekly measurement. It appeared that when the upper layers of soil were subjected to excessive drying by high temperatures and low humidity, there was a tendency toward equalization with the more moist underlying soil as the severe weather abated. The data were not sufficiently consistent to permit definite conclusions as to fluctuations within a week. Further evidence of such fluctuations, however, lies in the fact that seedlings died from drought during periods when the regular weekly morning soil-moisture measurements showed moisture content above the indicated wilting point. Also, on packed roadways and paths in the immediate vicinity of the plots moist spots sometimes showed up in early morning or after periods of cool, humid (not rainy) weather, and gradually disappeared when the atmosphere became hot and dry again.

Another point that must not be overlooked is that the moisture-holding capacity of soil on the average Douglas fir slash-burned area is extremely uneven. At points where large logs cross or where slash is very heavy, the slash fire becomes so hot that practically all the humus is burned out and the moisture-holding capacity of the soil is tremendously reduced. This was indicated by the variation in soil moisture of samples taken at different spots on area A during a hot,

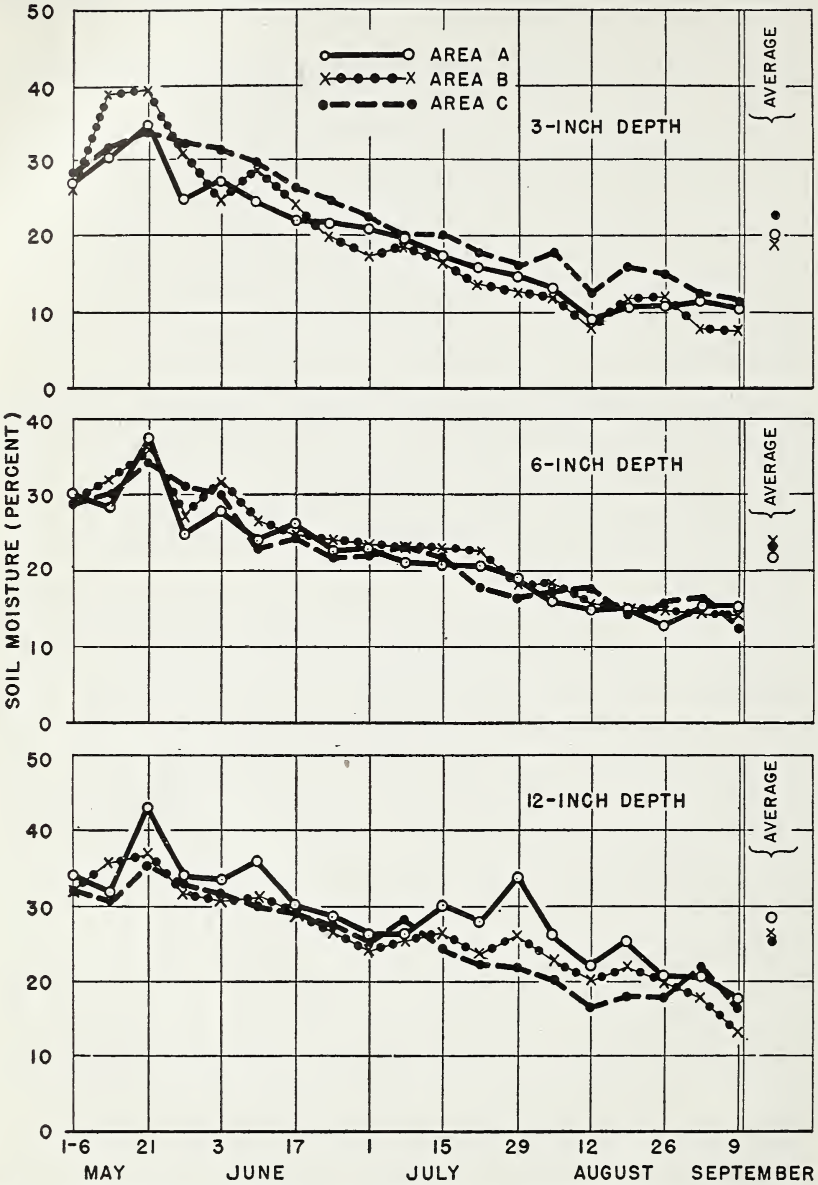
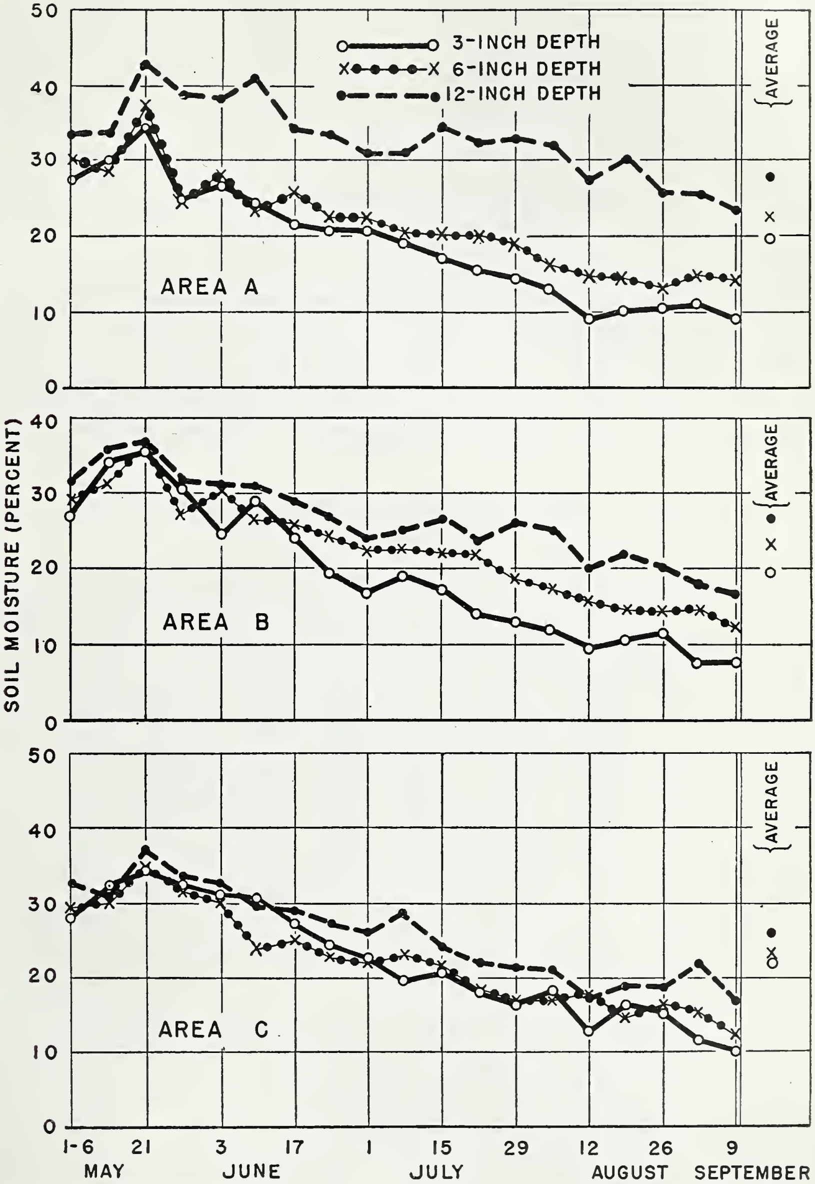


FIGURE 16.—Soil moisture, in terms of oven-dry weight of soil, at three different depths on areas A (in the by depth; graph on right, contrast by shade condition. Samples were taken in mornings at intervals of



open), B (in shade of dogwood bush), and C (under old-growth timber) in 1930: Graph on left, contrast approximately a week.

dry period in 1928, as previously described, and was definitely proved in a young plantation in the immediate vicinity of the plots. Here planted seedlings died and had to be replaced, in some instances for 4 successive years, on spots where it was noted the fire had been extremely hot, while on immediately adjacent ground, where there was evidence the fire had not been extremely hot, the first seedlings planted survived and made good growth. A soil analysis made in the soils department of the Washington State College showed a far greater reduction of humus content and moisture-holding capacity on the heavily than on the lightly burned spots.

## INFLUENCE OF EXPOSURE ON TEMPERATURE, EVAPORATION, AND SOIL MOISTURE

Measurements were made over a short period in August and September 1931 on areas adjacent to area A to determine the influence of exposure on temperature, evaporation, and soil moisture. Instrument set-ups similar to that on area A were installed on south, east, and west exposures, all within one-half mile. No north exposure was available. Data thus obtained on air and surface-soil temperatures, evaporation, and soil moisture are shown in tables 6, 7, and 8, respectively.

TABLE 6.—*Maximum air and surface-soil temperatures on different exposures, 1931*

| Day | Valley floor | | South exposure | | West exposure | | East exposure | |
|---|---|---|---|---|---|---|---|---|
| | Air | Surface | Air | Surface | Air | Surface | Air | Surface |
| | *°F.* | *°F.* | *°F.* | *°F.* | *°F.* | *°F.* | *°F.* | *°F.* |
| Aug. 4 | 101 | 143 | ---------- | 135 | ---------- | 131 | ---------- | ---------- |
| Aug. 8 | 84 | 138 | 96 | 153 | 84 | 131 | 101 | 140 |
| Aug. 10 | 97 | 139 | 107 | 156 | 101 | 142 | 106 | 149 |
| Aug. 12 | 88 | 140 | 102 | 139 | 88 | 147 | 101 | 129 |
| Aug. 15 | 88 | 136 | 95 | 143 | 86 | 136 | 90 | 142 |
| Aug. 17 | 100 | 152 | 109 | 156 | 100 | 141 | 99 | 154 |
| Aug. 22 | 100 | 148 | 111 | 150 | 103 | 140 | 104 | 148 |
| Aug. 24 | 95 | 147 | 108 | 153 | 96 | 137 | 97 | 152 |
| Aug. 27 | 91 | 142 | 105 | 152 | 92 | 137 | 95 | 147 |
| Sept. 1 | 95 | 134 | 109 | 155 | 96 | 139 | 101 | 152 |
| Sept. 3 | 95 | 149 | 109 | 156 | 96 | 133 | 100 | 151 |
| Sept. 8 | 91 | 146 | 106 | 148 | ---------- | 126 | ---------- | 148 |
| Average | 94 | 143 | 105 | 150 | 94 | 137 | 99 | 147 |

TABLE 7.—*Average daily evaporation on different exposures, 1931*

| Period | Valley floor | South exposure | West exposure | East exposure |
|---|---|---|---|---|
| | *Cc* | *Cc* | *Cc* | *Cc* |
| Aug. 11 to 12 | 29 | 32 | 29 | 30 |
| Aug. 13 to 15 | 33 | 42 | 35 | 34 |
| Aug. 16 to 17 | 36 | 50 | 42 | 36 |
| Aug. 18 to 22 | 29 | 38 | 33 | 28 |
| Aug. 23 to 24 | 35 | 50 | 42 | 40 |
| Aug. 25 to 27 | 33 | 42 | 38 | 31 |
| Aug. 28 to Sept. 1 | 33 | 45 | 38 | 35 |
| Sept. 2 to 3 | 32 | 45 | 32 | 30 |
| Sept. 4 to 8 | 19 | 24 | 22 | 20 |
| Average | 31 | 41 | 35 | 32 |

TABLE 8.—*Soil moisture at 3-, 6-, and 12-inch depths, on different exposures, 1931*

| Day | Valley floor | | | South exposure | | | West exposure | | | East exposure | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 inches | 6 inches | 12 inches | 3 inches | 6 inches | 12 inches | 3 inches | 6 inches | 12 inches | 3 inches | 6 inches | 12 inches |
| | *Percent* | *Percent* | *Per. cent* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* |
| Sept. 1 | 14.0 | 19.4 | 21.2 | 5.7 | 7.8 | 10.7 | 10.0 | 16.0 | 11.5 | 8.8 | 9.4 | 9.6 |
| Sept. 8 [1] | 11.8 | 15.8 | 23.0 | 7.5 | 8.9 | 11.8 | 13.9 | 15.8 | 10.8 | 9.0 | 9.6 | 11.1 |
| Average | 12.9 | 17.6 | 22.1 | 6.6 | 8.4 | 11.2 | 12.0 | 15.9 | 11.2 | 8.9 | 9.5 | 10.4 |

[1] Between Sept. 1 and Sept. 8, 0.43 inch of rain fell.

Air and surface-soil temperatures and evaporation were higher and soil moisture was lower on the south exposure than on the other exposures. These appeared to be the only consistent relations existing between these environmental factors and exposure. The west exposure was nearest to the south exposure in evaporation, and the east exposure was nearest to the south exposure in air and surface-soil temperatures and in soil moisture. The flat was consistently high in soil moisture. On the east and south exposures soil moisture was below the indicated wilting point at all depths.

The data indicate that the east and west exposures and the flat differ comparatively little in severity, but that the south exposure is much more severe than the other three.

## ROOT PENETRATION AND WILTING POINT OF SEEDLINGS

Observations made in connection with the study of soil moisture showed that root penetration of current-year seedlings on the study areas ranged from 3 to 12 inches, but that most of the feeder roots of the majority of seedlings were contained in the 5-inch soil zone lying between the depths of 2 and 7 inches. This, therefore, is the soil zone most important in determination of wilting coefficient. Wilting-point determinations were made, at several times during the study and with a total of 40 seedlings, by the following method: The soil surrounding a seedling was dug away so as to leave the seedling in a core of soil about 8 inches in diameter and 10 inches deep. This core was then wrapped with wire screen, a piece of board or tin was shoved under it, and it was raised and moved to a moderately exposed place where it was protected from the midday sun. When the 8-inch core had dried out to such a degree that permanent wilting of the seedling occurred, a 3-inch core, which contained most of the seedling roots, was taken out of the center of it and the moisture content of this smaller core was determined.

Some difficulty was experienced in determining just when wilting became permanent. Also, the wilting point of the seedlings was found to vary with current weather conditions and with ratio of crown size to root size. The first sign of fatal injury to a Douglas fir seedling by drought is a curling of the needles. Next the seedling begins to turn yellow. If it is very young it may tumble over, but more often it remains in an upright position when completely dried. Seedlings were listed as drought-killed when it was evident that drought was the final cause, even though there was evidence of previous injury from heat or other causes. The soil-moisture content at which wilting occurred varied from 5 to 12 percent of the oven-dry weight of the soil, and averaged about 10 percent of that weight.

The fact that some seedlings died from drought when the weekly morning soil sample showed a moisture content above wilting point, both during short periods of extremely severe weather and also during long continuous periods of moderate weather, is evidence that the wilting-point determinations did not tell the whole story. It must not be assumed that no drought losses took place at moisture contents above 12 percent and all seedlings died at moisture contents below 12 percent, or that moisture content everywhere on the area was the same as at the point sampled.

## SEEDLING GERMINATION, LOSSES, AND SURVIVAL

### SEEDLING RECORDS TAKEN

An individual record was kept of every Douglas fir seedling [10] on the plots, except a few that were removed from spots where seedlings occurred so thickly as to cause confusion in numbering. When each seedling germinated, it was given a number [11] and a record was made of the date of germination, type of surface soil, and degree of shade. Surface-soil types recognized were (1) natural mineral soil, (2) mineral soil with charcoal surface, (3) charred duff, and (4) rotten wood; and degrees of shade noted were none, medium, and dense. Classification as to shade was not changed as the season progressed. A seedling was classified as completely exposed to the sun if when it germinated there was no immediate prospect of shade from growing vegetation. In many cases, later in the season such a seedling was subject to some shade because of the growth of weeds and brush. Seedlings were examined weekly, or oftener in critical weather, and when failure occurred the cause was recorded, if it could be determined. When a seedling died it was removed.

### GERMINATION

Since natural seeding in the locality of the study areas could not be depended upon to produce Douglas fir seedlings in numbers sufficient for the purposes of the study, Douglas fir seed was sown on the study plots in the fall or winter of each year beginning with 1926. In 1927 only one seedling germinated on the plots. The seed had been sown broadcast, and presumably had been eaten by birds or rodents. In 1927–30, seed was sown in spots and covered with screens. Some of the seed sown in 1928–30 was eaten by mice, which dug under the screens. The number of seedlings germinating in each of the years 1928–31 is shown in table 9.

On areas A and B germination occurred in late May and early June 1928; after May 12, 1929; in late April and early May 1930; and soon after June 9, 1931. Such germination as took place on area C occurred 4 to 6 weeks later than germinaton of the same year on areas A and B.

On area C germination totaled only 29 seedlings for the 4 years, and so was not studied and tabulated along with that on areas A and B.

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[10] In addition to Douglas fir seedlings there were present on the plots a few tree seedlings of the other species occurring in the old-growth forests of the vicinity, but none of the latter was included in this study.

[11] The seedling markers designed for this study, which served very satisfactorily, are shown in fig. 19, p. 41. Each marker consisted of an 18-inch No. 9 wire stake with a 1-inch (spot-welded) loop at one end and a number tag of ½-inch aluminum tape. The aluminum tag was attached to the wire stake by passing one end of the tag through the loop and giving the stake a half turn. The tag then formed a little flag, extending at right angles to the stake, that was very easy to see and read. The stakes were made by a wire company for approximately 1 cent each. Tops of stakes were dipped in paint, the color designating the year when the seedling germinated.

TABLE 9.—*Seedlings germinating on cut-over areas*[1] *in each year of the period 1928–31, by degree of shade*

| Area and year | No shade | Medium shade | Dense shade | Total |
|---|---|---|---|---|
| A:[2] | *Number* | *Number* | *Number* | *Number* |
| 1928 | 358 | 174 | 48 | 580 |
| 1929 | 108 | 17 | 6 | 131 |
| 1930 | 85 | 37 | 20 | 142 |
| 1931 | 85 | 65 | 14 | 164 |
| Total | 636 | 293 | 88 | 1,017 |
| B:[3] | | | | |
| 1928 | 46 | 73 | 82 | 201 |
| 1929 | 8 | 5 | 11 | 24 |
| 1930 | 123 | 137 | 86 | 346 |
| 1931 | 7 | 7 | 31 | 45 |
| Total | 184 | 222 | 210 | 616 |
| A and B: | | | | |
| 1928 | 404 | 247 | 130 | 781 |
| 1929 | 116 | 22 | 17 | 155 |
| 1930 | 208 | 174 | 106 | 488 |
| 1931 | 92 | 72 | 45 | 209 |
| Total | 820 | 515 | 298 | 1,633 |

[1] On 3 sample plots, 6.6 by 132 feet, on each area. On the plots on area C (old-growth timber) only 29 seedlings germinated, as follows: 1929, 7; 1930, 10; and 1931, 12.

[2] Open burn.

[3] Brush-covered burn.

## FIRST-SEASON LOSSES

Seedling mortality was found to be far greater in the first year than later; therefore first-season losses will be discussed separately for each of the 4 years 1928–31, as to proportions, causes, and distribution by degree of shade. Data on seedling losses according to type of surface soil brought out no point other than that losses from heat injury were considerably greater on the charred surfaces; accordingly, such data are not presented except in an account of a special study of mortality on different-colored soils. In studying seedling losses it must be borne in mind that in 1928, when the first seedlings of the study germinated, area A was a 3-year-old burn and area B an 8-year-old burn, and that in the following years cover density gradually increased on both areas.

For several days following germination, Douglas fir seedlings, according to the records of this study, are liable to fatal heat injury (sometimes called sunscald or heat lesions) if their stems are subjected to a temperature of 125° F. or more. Some seedlings are more susceptible than others, and some remain tender for weeks whereas others harden quickly. Some seedlings in the latter part of their first season were exposed to surface temperatures as high as 150° for short periods and continued to live. The term "heat injury," as used in this study, applies only to injury to the cambium in the seedling stem, usually at the ground surface. It does not include the general drying up of seedlings that results from the combined effect of heat and drought.

During 1928, while this study was in progress with seedlings on cut-over lands, a study of heat injury to seedlings was made in the Wind River nursery[12] of the Forest Service. There it was found that seedlings up to 20 days old may be injured and killed by surface temperatures of 125° F., and that seedlings less than 16 days old may be injured and killed by temperatures as low as 123°. It was also found that tender seedlings taken from seedbeds in their second season and placed in unshaded transplant beds are often injured and killed by such surface temperatures as develop there.

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[12] KAUFERT, F. REPORT ON HEAT INJURY IN SEEDBEDS AND TRANSPLANTS. U. S. Forest Serv., North Pacific Region. file memorandum. 1929.

Two definite points must be kept in mind regarding seedling losses by heat in this study: (1) Of the seedlings that germinated on surfaces completely exposed to sunlight, all but a few were killed off early in the season and most of the survivors received some shade from weeds in the latter part of the season; (2) many seedlings that were injured by heat early in the season later died from drought, and were listed as drought-killed although heat injury was a contributing cause of their loss. The fact that losses from heat injury did not occur late in the season as well as early in the season is amply explained by the fact that no seedlings then remained in complete exposure.

It was impossible definitely to segregate effect of shade of slash from effect of shade of vegetation; but it was specifically noted that mortality was less in "dead" shade (shade of logs and slash) than in "living" shade (shade of vegetation). This is explained by the fact that neighboring vegetation competes with seedlings for moisture and plant food.

Findings as to the soil-moisture content at which seedlings may die of drought are given in the preceding section (p. 29). Probably drought would head the causes of loss if it were not for the fact that many seedlings were killed by heat and other factors before the annual drought period came on.

Losses listed under "insects and other causes" in this study included those from (1) frost injury, which occurred at air temperatures of 30° F. or less; (2) mice, which nipped off seedlings just above the ground; (3) cutworms and strawberry weevil; (4) competition of other vegetation; and (5) mechanical injury. Fungi are not known to have caused any seedling loss in this study; forest pathologists[13] of the Bureau of Plant Industry cooperating in the study found no evidence of losses from disease, and none was noted by the men taking the records. The fact that the seedlings were widely scattered on a natural soil surface, not crowded in seedbeds, may have prevented disease losses.

Seedling losses in each of the years 1928 to 1931 are shown by cause and by shade intensity at time of germination in tables 10, 11, and 12.

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[13] F. Kaufert, who in 1928 was studying mortality due to damping-off in the Wind River nursery of the Forest Service and examined microscopically many dead seedlings from the plots used in this study, and H. G. Lachmund, who examined dead seedlings from the plots from time to time during the 1929, 1930, and 1931 seasons.

TABLE 10.—*First-year losses of seedlings on cut-over areas in each year of period 1928–31 by degree of shade*

| Area and year | No shade | Medium shade | Dense shade | Total |
|---|---|---|---|---|
| | *Percent* | *Percent* | *Percent* | *Percent* |
| A:[1] | | | | |
| 1928 | 91 | 77 | 25 | 81 |
| 1929 | 96 | 88 | 50 | 93 |
| 1930 | 100 | 86 | 70 | 92 |
| 1931 | 89 | 58 | 43 | 73 |
| Weighted average | 93 | 75 | 40 | 83 |
| B:[2] | | | | |
| 1928 | 100 | 52 | 17 | 49 |
| 1929 | 62 | 80 | 18 | 46 |
| 1930 | 100 | 100 | 83 | 96 |
| 1931 | 100 | 43 | 26 | 40 |
| Weighted average | 98 | 82 | 45 | 74 |
| A and B: | | | | |
| 1928 | 92 | 70 | 20 | 73 |
| 1929 | 94 | 86 | 29 | 86 |
| 1930 | 100 | 97 | 80 | 95 |
| 1931 | 90 | 57 | 31 | 66 |
| Weighted average | 94 | 78 | 44 | 80 |

[1] Open burn.
[2] Brush-covered burn.

TABLE 11.—*First-year losses of seedlings on cut-over areas in each year of period 1928–31, by cause*

| Area and year | Heat[1] | Drought | Insects and other | Total |
|---|---|---|---|---|
| | *Percent* | *Percent* | *Percent* | *Percent* |
| A:[2] | | | | |
| 1928 | 59 | 18 | 4 | 81 |
| 1929 | 69 | 12 | 12 | 93 |
| 1930 | 0 | 18 | 74 | 92 |
| 1931 | 0 | 73 | 0 | 73 |
| Weighted average | 43 | 26 | 14 | 83 |
| B:[3] | | | | |
| 1928 | 17 | 28 | 4 | 49 |
| 1929 | 17 | 17 | 12 | 46 |
| 1930 | 1 | 10 | 85 | 96 |
| 1931 | 0 | 40 | 0 | 40 |
| Weighted average | 7 | 18 | 49 | 74 |
| A and B: | | | | |
| 1928 | 48 | 21 | 4 | 73 |
| 1929 | 62 | 12 | 12 | 86 |
| 1930 | 0 | 13 | 82 | 95 |
| 1931 | 0 | 66 | 0 | 66 |
| Weighted average | 29 | 23 | 28 | 80 |

[1] In 1928 and 1929 the losses from heat injury occurred within a month after germination.
[2] Open burn.
[3] Brush-covered burn.

TABLE 12.—*First-year losses of seedlings on cut-over areas during whole of period 1928–31, by cause and by degree of shade*

| Area and cause of loss | No shade | Medium shade | Dense shade | Total |
|---|---|---|---|---|
| | *Percent* | *Percent* | *Percent* | *Percent* |
| A:[1] | | | | |
| Heat | 55 | 29 | 0 | 43 |
| Drought | 22 | 37 | 22 | 26 |
| Insects and other | 16 | 9 | 18 | 14 |
| Total | 93 | 75 | 40 | 83 |
| B:[2] | | | | |
| Heat | 15 | 5 | 0 | 7 |
| Drought | 24 | 21 | 11 | 18 |
| Insects and other | 59 | 56 | 34 | 49 |
| Total | 98 | 82 | 45 | 74 |
| A and B: | | | | |
| Heat | 46 | 19 | 0 | 29 |
| Drought | 23 | 30 | 14 | 23 |
| Insects and other | 25 | 29 | 30 | 28 |
| Total | 94 | 78 | 44 | 80 |

[1] Open burn.

[2] Brush-covered burn.

### LOSSES IN 1928

The definite indications brought out by data on first-season losses of seedlings in 1928 on areas A and B are as follows:

1. Heat injury caused the greatest loss, killing 48 percent of all the seedlings. Most of the mortality from heat injury occurred during a hot, dry period in late May and early June. The percentage of loss from this cause on area A was more than triple that on area B, where there was more shade and less of exposed, charred surface.

2. Drought caused the second greatest loss, killing 21 percent of the seedlings. Mortality from this cause was lowest on area A, where most of the seedlings, particularly on fully exposed surfaces, were killed by heat before they were subjected to drought. The heaviest losses from drought occurred in medium and dense shade. Had all seedlings remained alive until the drought period began, presumably the heaviest loss from drought would have occurred in the open.

3. Loss from insects and other causes included only 4 percent of the seedlings on each area.

4. Losses included 92 percent of the seedlings on fully exposed surfaces, 70 percent of those in medium shade, and 20 percent of those in dense shade, and totaled 73 percent of all seedlings.

### LOSSES IN 1929

First-year losses of seedlings in 1929 were greater than those in 1928, but resembled them in many respects. Findings on areas A and B were as follows:

1. As in 1928, heat injury caused the greatest loss, killing 62 percent of all the seedlings. It occurred in late May.

2. Drought loss again was great, totaling 12 percent. The fact that it was less than in 1928 is probably attributable to the fact that more of the seedlings were killed by heat before being subjected to drought than in 1928.

3. Loss from insects and other causes totaled 12 percent, as compared with 4 percent in 1928. Most of this loss was from cutworms and strawberry weevils.

4. Losses included 94 percent of the seedlings on fully exposed surfaces, 86 percent of those in medium shade, and 29 percent of those in dense shade, and totaled 86 percent.

Of the seven seedlings that germinated on area C (under old-growth timber), all died within 6 weeks, apparently from inadequacy of light, soil moisture, and heat.

### LOSSES IN 1930

In 1930, first-season losses of seedlings on areas A and B were an entirely different story from what they had been in the 2 previous years.

1. Loss from heat injury amounted to less than 1 percent. The reasons for this were the coolness of the spring weather and the fact that early in the season all the remaining unshaded seedlings were killed by factors other than heat.

2. Loss from drought totaled 13 percent, nearly the same as in 1929.

3. Loss charged to insects and other causes jumped into a long lead, amounting to 82 percent, and new major causes of seedling loss under this classification were manifest. About May 5, when germination was not yet complete, the screens were removed from the seed spots where seedlings were germinating. Within the next few days three-fourths of the seedlings were destroyed by mice [14] and frost,[15] the mice taking about one-half and the frost about one-fourth of the total number that germinated.

4. Losses included 100 percent of the seedlings on fully exposed surfaces, 97 percent of those in medium shade, and 80 percent of those in dense shade. The total loss for the season on areas A and B was 95 percent. This was the greatest loss for any of the 4 years during which seedling loss was recorded.

Of the 10 seedlings that germinated on area C in 1930, 5 were nipped off by mice and the remaining 5 died before the end of July.

### LOSSES IN 1931

In 1931, first-season loss of seedlings on areas A and B was significantly lighter than in the previous years and the loss was attributed wholly to a single cause that had not been a major cause of loss in any of the previous years.

1. No loss was charged to heat injury. During a period in late May and early June surface temperatures high enough to kill seedlings occurred, but germination had not yet begun. Such temperatures did not occur again until mid-July, by which time the surviving seedlings had hardened and additional cover had developed. Many seedlings showed evidence of heat injury.

2. Drought appeared to be the final cause of all seedling loss. It took 66 percent of the seedling crop.

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[14] The mice nipped the seedlings off during the night. Live traps were constructed, seedlings in place being used for bait. The following night a mouse was caught in every trap. Specimens caught were identified by Stanley Jewett, of the Bureau of Biological Survey, as the white-footed mouse (*Peromyscus maniculatus austerus*). Poison was spread, and destruction of seedlings by mice stopped immediately.

[15] Between May 6 and May 13 daily minimum air temperatures went down to 27° and 26° F., and daily minimum surface-soil temperatures in exposed spots went down to 23°, killing many seedlings. The frost affected primarily the portion of the stem near the ground surface, rupturing the cells and causing the stem to collapse. In many instances the injury so closely resembled heat injury, even as seen under a microscope, that in the absence of temperature records the cause could not have been determined with certainty. Loss was noticeably heavier in the open than under plant cover.

3. Losses included 90 percent of the seedlings on fully exposed surfaces, 57 percent of those in medium shade, and 31 percent of those in dense shade.

The record for area C in 1931 was about the same as in previous years; of the 12 seedlings that germinated, 3 were eaten by mice and the remaining 9 died before September 1.

### SUMMARY OF FIRST-SEASON LOSSES

In every year the heaviest losses occurred on the fully exposed surfaces, and in 3 of the 4 years the losses were decidedly heavier on area A than on area B (table 10). In the year when the losses were heavier on area B, most of them were caused by mice and frost. Heat injury took first place as a cause of loss in 1928 and 1929, insects and other causes in 1930, and drought in 1931 (table 11). Losses included 94 percent of the seedlings on fully exposed surfaces, 78 percent of those in medium shade, and 44 percent of those in dense shade (table 12).

On area C, the 29 seedlings that germinated (4 to 6 weeks after germination occurred in the open) died within 2 months. Some were eaten by mice. The cause of death of the remainder was not definitely determined, but was believed to be inadequacy of light, heat, and soil moisture.

Right here a significant point arises regarding the importance of shade in seedling establishment. We have on the one hand a 94-percent first-year seedling loss on fully exposed cut-over surfaces, a 78-percent loss on medium-shaded cut-over surfaces, and a 44-percent loss on densely shaded cut-over surfaces; on the other hand we have a 100-percent seedling loss in the shade of virgin timber. The records of solar radiant energy indicated that when full sunlight was given a value of 100 percent the light on a surface densely shaded by brush had a value of 66 percent and that on a surface shaded by old-growth timber had a value of 2 percent. The optimum shade condition for seedling establishment is not exactly indicated; but the study does show that a shade condition having a light value of 66 percent of full sunlight is far more favorable to seedling survival than either the very heavy shade of virgin timber, having a light value of 2 percent, or complete exposure, the light value of which is considered as 100 percent.

### LOSSES AND SURVIVAL OF 1928–30 SEEDLING CROPS OVER PERIOD 1928–31

Losses and survival of seedlings of the 1928–30 crops over the 4-year period 1928–31 are shown in table 13 by years and according to degree of shade at time of germination.

Of the seedlings that germinated in 1928 on area A, only 11 percent were still alive at the end of the fourth year. The survivors included 1.5 percent of the seedlings occurring on fully exposed surfaces, 13 percent of those in medium shade, and 67 percent of those in dense shade. On area B losses of 1928 seedlings during the 4 years were considerably less, 35 percent surviving. The survivors included 26 percent of the seedlings occurring in medium shade, 62 percent of those in dense shade, and none of those on fully exposed surfaces.

**TABLE 13.**—*Losses and survival over period 1928–31 of seedlings germinating in period 1928–30 on areas A and B, by degree of shade*

| Item | Area A [1] | | | | Area B [2] | | | | Areas A and B | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No shade | Medium shade | Dense shade | All degrees of shade | No shade | Medium shade | Dense shade | All degrees of shade | No shade | Medium shade | Dense shade | All degrees of shade |
| | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* | *Pct.* |
| Seedlings of 1928 crop lost in— | | | | | | | | | | | | |
| 1928 | 91 | 77 | 25 | 81 | 100 | 52 | 17 | 49 | 92 | 70 | 20 | 73 |
| 1929 | 7 | 8 | 8 | 7 | ----- | 11 | 15 | 10 | 6 | 9 | 12 | 8 |
| 1930 | .5 | 2 | 0 | 1 | ----- | 10 | ----- | 3 | .5 | 4 | 0 | 2 |
| 1931 | 0 | 0 | 0 | 0 | ----- | 1 | 6 | 3 | 0 | .4 | 4 | 1 |
| Total lost | 98.5 | 87 | 33 | 89 | 100 | 74 | 38 | 65 | 98.5 | 83.4 | 36 | 84 |
| Surviving at end of 1931 | 1.5 | 13 | 67 | 11 | 0 | 26 | 62 | 35 | 1.5 | 16.6 | 64 | 16 |
| Seedlings of 1929 crop lost in— | | | | | | | | | | | | |
| 1929 | 96 | 88 | 50 | 93 | 62 | 80 | 18 | 46 | 94 | 86 | 29 | 86 |
| 1930 | 4 | 6 | 0 | 4 | 38 | 0 | 55 | 37 | 6 | 5 | 35 | 9 |
| 1931 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total lost | 100 | 94 | 50 | 97 | 100 | 80 | 73 | 83 | 100 | 91 | 64 | 95 |
| Surviving at end of 1931 | 0 | 6 | 50 | 3 | 0 | 20 | 27 | 17 | 0 | 9 | 36 | 5 |
| Seedlings of 1930 crop lost in— | | | | | | | | | | | | |
| 1930 | 100 | 86 | 70 | 92 | 100 | 100 | 83 | 95.7 | 100 | 97 | 80 | 95 |
| 1931 | ----- | 0 | 5 | .7 | ----- | ----- | 1 | .3 | 0 | 0 | 2 | .4 |
| Total lost | 100 | 86 | 75 | 92.7 | 100 | 100 | 84 | 96.0 | 100 | 97 | 82 | 95.4 |
| Surviving at end of 1931 | 0 | 14 | 25 | 7.3 | 0 | 0 | 16 | 4.0 | 0 | 3 | 18 | 4.6 |

[1] Open burn.

[2] Brush-covered burn.

The loss of 1929 seedlings on area A totaled 97 percent in the first 2 years. The 3 percent surviving at the end of 3 years included 6 percent of the seedlings occurring in medium shade, 50 percent of those in dense shade, and none of those on fully exposed surfaces. For this crop likewise, on area B the loss by the end of 1931 was much less, 17 percent surviving. The survivors included 20 percent of the seedlings occurring in medium shade, 27 percent of those in dense shade, and none of those on fully exposed surfaces.

The loss of 1930 seedlings on area A in the first 2 years totaled about 93 percent. The 7 percent surviving at the end of 1931 included 14 percent of the seedlings occurring in medium shade, 25 percent of those in dense shade, and none of those on fully exposed surfaces. On area B the 4 percent surviving at the end of 1931 included 16 percent of the seedlings occurring in dense shade and none of the others.

One significant point brought out previously and emphasized by the summary of seedling losses on areas A and B is the fact that of the seedlings germinating in 1928, 1929, and 1930 on fully exposed surfaces, which originally totaled 728, none was alive at the end of 1931 except 6 of the 1928 seedlings on area A, whereas of the seedlings germinating in dense shade, originally totaling 253, 108 survived. In this connection it must be remembered that all seedlings were produced by planting seed in spots and that consequently even seedlings occurring in dense shade usually had ample root space the first few years.

## SEEDLING-LOSS HISTORIES WITH PARALLEL WEATHER AND SOIL-MOISTURE RECORDS

In order to show relations of meteorological factors to seedling losses, periodic first-year losses on area A were plotted together with daily maximum air and surface temperatures, rainfall, evaporation, and soil-moisture content at a depth of 3 inches, for the growing seasons of 1928 and 1931, respectively. The resulting graphs appear as figures 17 and 18.

In 1928 (fig. 17) germination occurred in late May and early June. Surface-soil temperatures up to 139° F. produced on June 10 and 11, when maximum air temperature was 90°, caused an immediate seedling loss of more than 41 percent from heat injury; during the next few days injured seedlings continued to die until the loss totaled 53 percent, although the weather of those days was cool and moist. Favorable weather continued and seedling losses gradually lessened until July 8, when the hot, dry midsummer period began. The remaining seedlings, mostly on shaded surfaces, had now hardened, and losses from this date on were caused not by heat but by drought. Evaporation increased, and soil-moisture content at the 3-inch depth gradually decreased to less than 10 percent and remained below that point for several weeks. During the first week of August losses again lessened, although the drought continued; but this was due to the fact that few seedlings were left. Heavy losses recorded on August 29 and September 7 actually occurred during preceding weeks; the seedlings withered during those weeks, but could be recorded as dead only when rains came and they failed to revive.

The record for 1931 (fig. 18) is an entirely different story. Germination occurred along with rain and cool weather that began June 10, and when summer drought began in July some cover had developed and the seedlings had hardened sufficiently to become somewhat resistant to heat. During late June and early July a few weak seedlings in the most exposed spots died in an erect position, although temperatures were low, there was no evidence of heat lesions, and the weekly soil sample showed ample moisture. The deaths were classified as drought losses, although the cause was doubtful. After the first few weeks of drought, and throughout the remainder of the season, drought losses were heavier than in previous years, because very few seedlings had been killed off early in the season by heat, frost, or other causes. A slight drop in temperature during the week ending August 10 caused dying seedlings to remain alive until temperatures went up again on August 17. The seedlings recorded as dead on September 8 and 14 actually died during the preceding drought period, but their death could be verified only when fall rains occurred and they failed to revive. As in 1928, the evaporation curve remained high and the soil-moisture curve gradually sank until the beginning of fall rains. Only 0.04 inch of rain fell between the last of June and the second week of September. At no time during the season, however, was soil-moisture content observed to have dropped to the indicated wilting point for this soil (12 percent). It appears that such protracted drought is capable of killing seedlings even if soil-moisture content remains above the danger point indicated by determinations made in this study.

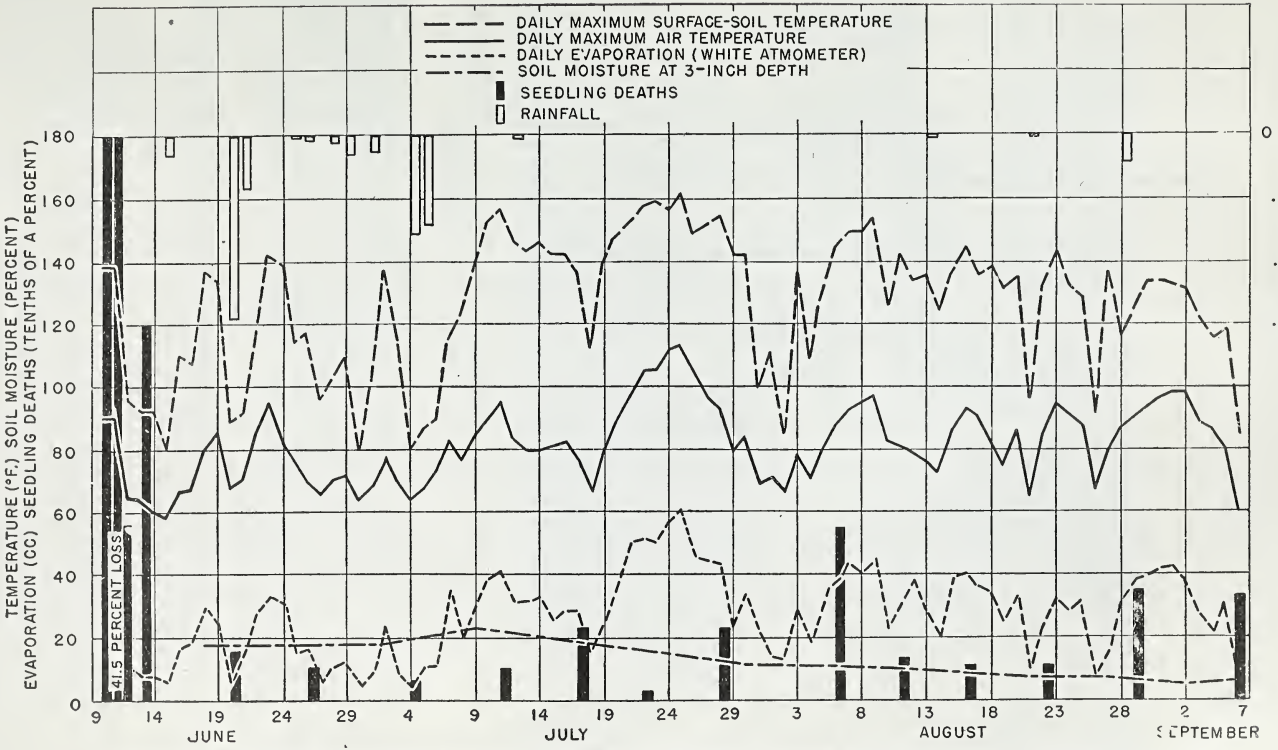

FIGURE 17.—Periodic first-year seedling losses on area A in 1928 and concurrent temperatures, evaporation, rainfall, and soil moisture content.

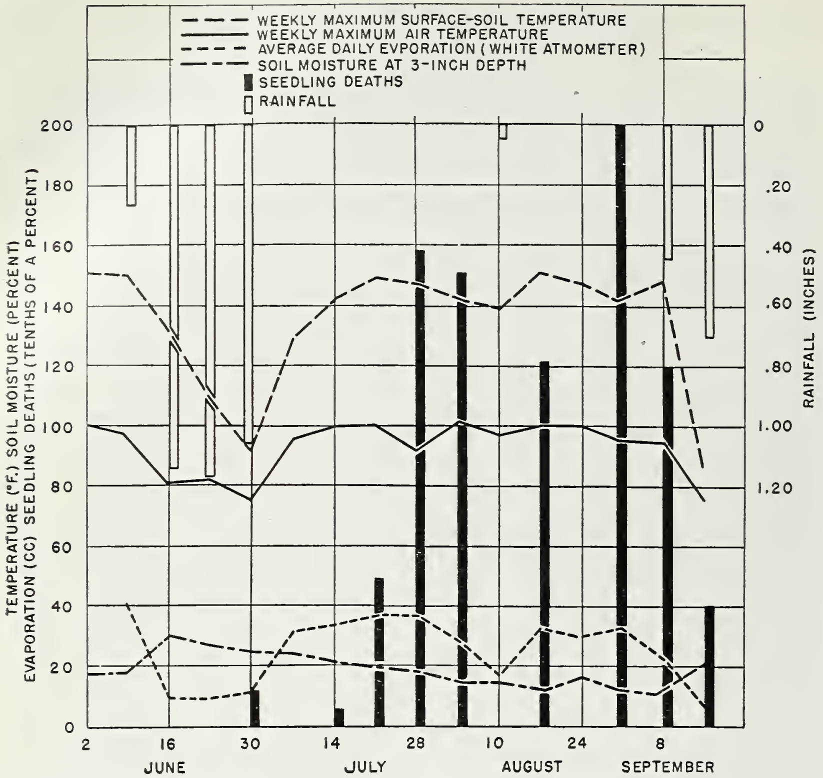

FIGURE 18.—Periodic first-year seedling losses on area A in 1931 and concurrent temperatures, evaporation, rainfall, and soil-moisture content.

## LOSSES ON YELLOW AND BLACK SOILS AND TEMPERATURES AT WHICH THEY OCCURRED

Seedling mortality and survival were studied on area A on a natural yellow soil surface and on an adjacent soil surface that was blackened by charcoal from the slash fire. Germination took place in the 5-day period May 13–17, 1929, and the seedlings were numbered and staked immediately (fig. 19). None of the seedlings on the surfaces were shaded, although small clumps of vegetation were present. The losses are shown in table 14.

TABLE 14.—*Seedling losses on an unshaded black (charcoal) soil surface and a comparable adjoining unshaded natural yellow soil surface, on area A, 1929*

| Date [1] of observation | Maximum air temperature | Black surface | | | Yellow surface | | |
|---|---|---|---|---|---|---|---|
| | | Maximum temperature | Seedling loss | | Maximum temperature | Seedling loss | |
| | | | Daily | Total | | Daily or periodic | Total |
| | *°F.* | *°F.* | *Percent* | *Percent* | *°F.* | *Percent* | *Percent* |
| May 20 | 89 | 143 | 47 | 47 | 125 | 0 | 0 |
| May 21 | 85 | 144 | 6 | 53 | 135 | 16 | 16 |
| May 22 | 89 | 144 | 47 | 100 | 137 | 0 | 16 |
| May 23 | 83 | 134 | | | 122 | 16 | 32 |
| May 24 | 81 | 133 | | | 121 | 0 | 32 |
| Oct. 1 | | | | | | 57 | 89 |

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[1] Germination took place in the 5-day period May 13–17.

On May 20, the first day when the maximum air temperature was as high as 89° F., the temperature on the black soil surface rose to 143° and took a toll of 47 percent of the seedlings, while that on the yellow soil surface rose only to 125° and caused no seedling deaths, although it caused some injury. By the end of the third day with a temperature of 85° to 89°, all the seedlings on the black surface were dead, while on the yellow soil the loss totaled only 16 percent. Many of the remaining seedlings died on the fourth day, bringing the loss on the yellow soil up to 32 percent.

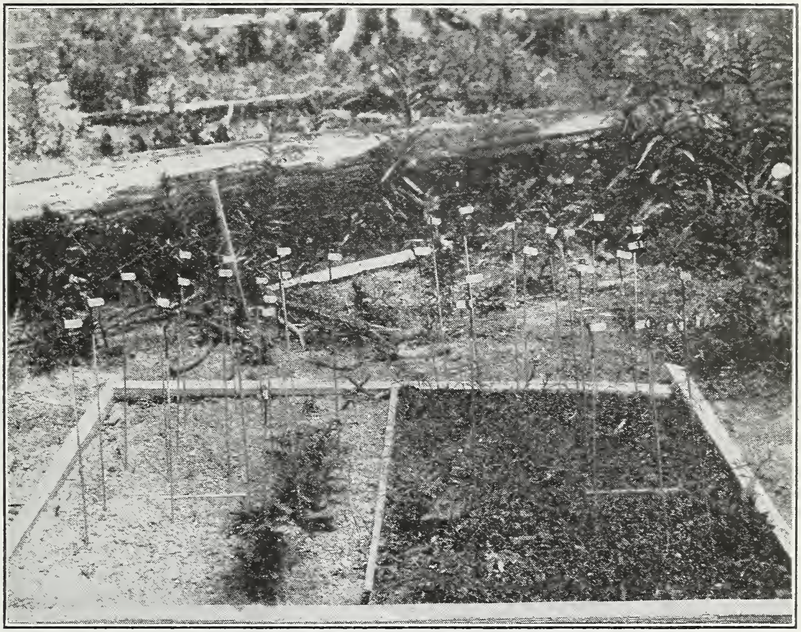

FIGURE 19.—Subplots on area A having black and yellow soil surfaces, respectively, where surface temperatures and accompanying seedling losses were compared. Seedling markers are shown in place before any seedling deaths occurred.

Heat injury was first noticed when the surface temperature reached 123° F., but heat deaths did not occur until the temperature went to 125°. The seedlings surviving the surface temperature of 137° that occurred on the yellow surface on May 22 all showed evidence of heat injury; nevertheless 11 percent of the seedlings that germinated on this surface were still alive at the end of the season.

## SUMMARY AND RECOMMENDATIONS

Douglas fir (*Pseudotsuga taxifolia* (Lamb.) Britt.) seedling establishment and loss in relation to certain environmental factors were studied on a flat in the upper Wind River Valley near Carson, Wash. Three adjoining areas were selected, of which one had recently been cut over and severely slash-burned and had practically no plant cover, one had been cut over and lightly burned 5 years earlier and had a moderately heavy brush cover, and the third was a strip of virgin forest separating the first two. In site and other conditions affecting seedling establishment these areas are approximately typical of most of the forest land in the Douglas fir region. Three parallel plots, 6.6 by 132 feet, were established on each area. Because natural seeding was inadequate, seedlings were produced by sowing seed in spots, which were then covered with screens to prevent seed destruction by rodents prior to germination. Data on air and soil temperatures, precipitation, evaporation and solar radiant energy, soil moisture, and other environmental factors, and on seedling losses and survival are presented for the 4 years 1928–31, with some meteorological data for 1927.

Under the conditions studied temperature, particularly that of the surface soil, formed the most important link in the chain of environmental factors governing seedling establishment. It caused more first-year losses than any other environmental factor studied.

A surface-soil temperature of 123° F. for several days following germination is likely to injure Douglas fir seedlings and one of 125° or more is likely to kill them. Some seedlings are more susceptible than others, and some remain tender for weeks whereas others harden quickly. Temperatures in the neighborhood of 123° occur on natural soil surfaces when air temperatures are in the neighborhood of 80°, and such air temperatures are not uncommon in the region even during the first half of the growing season. Heat occurring early in the season killed 48 percent of the total number of seedlings on the cut-over areas in 1928, and 62 percent in 1929. Maximum surface temperatures were considerably higher in the open than in shade, and in the open they were higher on a fire-blackened soil surface than on a natural soil surface. On the first hot day in 1929, when air temperature rose to 89°, the temperature of an unshaded fire-blackened soil surface rose to 143° and killed 47 percent of the Douglas fir seedlings present, while that of an adjacent unshaded natural yellow soil surface rose only to 125° and caused no immediate seedling loss. Within the next 2 days, which had maximum air temperatures of 85° and 89°, the surface temperature of the black soil rose to 144° and killed all the remaining seedlings, while that of the yellow soil did not go above 137° and killed only 32 percent of the seedlings, although it injured many others.

Minimum temperatures, also, were an important factor. Early in May 1930, about 25 percent of the seedlings on the cut-over areas were killed by frost when on several nights air temperatures went down to 27° and 26° F. and surface-soil temperatures, in exposed spots, went as low as 23°.

The second most important environmental factor governing seedling establishment was soil-moisture content, which is controlled by precipitation and evaporation. Wilting-coefficient tests indicated that first-year seedlings would die of drought at moisture contents up to 12 percent of oven-dry weight of soil. The wilting point averaged 10 percent; it varied with atmospheric conditions and among individual seedlings. Drought losses of first-year seedlings on the cut-over areas averaged 23 percent for the four seasons and totaled 66 percent in 1931. Probably drought would head the causes of loss if it were not for the fact that many seedlings were killed by heat and other factors before the annual drought period came on.

In the locality of the study areas and generally throughout the Douglas fir region, in most years nearly all the precipitation comes in the fall, winter, and spring. July or August rainfall amounts to 0.1 inch or less almost as often as it exceeds that total. The moisture available for seedling growth, therefore, is mostly water stored in the soil from precipitation occurring previous to the seedlings' growing season. Evaporation is high during the dry season, particularly in the open. The daily loss from a white Livingston cup atmometer in the open averaged 27.8 cc; under a brush cover it was 38 percent less, and under virgin timber it was 46 percent less.

Each season the soil-moisture content decreased progressively through midsummer. It consistently averaged greater at the 12-inch depth than at the 3-inch depth, on all areas. It averaged less at the 3-inch depth and greater at the 12-inch depth in the open than on either the brush-covered or the old-growth timber area. At no time during the four growing seasons did the weekly soil sample show a moisture content of less than 12 percent at the 6-inch or the 12-inch depth; at the 3-inch depth, however, a moisture content of less than 12 percent was shown by some measurements during each of the four seasons on the cut-over areas, including all the measurements on the open area for 7 consecutive weeks during 1928.

Other factors that caused seedling losses included mice, cutworms, strawberry weevil, and mechanical injury. No great loss from any of these causes occurred except in 1930, when mice killed about 50 percent of the seedlings on the cut-over areas.

Measurements made on areas adjacent to the main study areas showed that aspect is an important factor in seedling establishment. The southerly exposure proved to be much more severe than the others.

The importance of shade, brought out in the discussions of temperature and evaporation, is further emphasized in the records of seedling germination and survival. On the old-growth timber area, where shade was extremely dense, germination took place a month or more after it did on the cut-over areas, and all seedlings died within their first season. First-year losses on the cut-over areas for the 4 years 1928–31 averaged 80 percent. They totaled 94 percent in the open, 78 percent on surfaces with medium shade, and 44 percent on surfaces with dense shade. Shade protects the seedlings not only from heat and drought but from frost as well; most of the losses from frost occurred in the open. It was definitely observed in the field that mortality was less in "dead" shade (shade of slash and logs) than in "living" shade (shade of vegetation, which competes with seedlings for moisture and plant food). The shade condition in which the highest percentage of seedling establishment occurred is that referred to as "dense shade" on cut-over land; it was found to have a light value of 66 percent of full sunlight.

Of the seedlings on the cut-over areas that survived their first season, which as has been shown averaged only 20 percent of each year's crop, many died in their second, third, and fourth years. The total loss of 1928–30 seedlings during the 4-year period 1928–31 was 89.1 percent.

The data indicate that under conditions such as now exist on the cut-over areas studied, and on most other areas in the Douglas fir region after logging and slash burning, Douglas fir seedling losses are so high as almost to preclude rapid natural restocking unless special measures are taken to bring it about. Most of the losses result from a combination of ground and weather conditions. Since nothing can be done about the weather, the chief means of bringing about better restocking is to provide more favorable ground conditions for seedling establishment through modification of logging practice.

The findings show clearly that slash fires produce site conditions that are unfavorable to seedling survival; through consumption of slash and duff and blackening of the surface soil they increase surface temperatures and evaporation and thereby increase seedling losses from the two principal causes—heat and drought. On some entire cut-over areas and on parts of most of them, the slash is so heavy that fire protection without some slash burning is out of the question and there is insufficient room for seedlings. In such cases slash burning, by preventing accidental fires and making more mineral soil available for germination, is likely to result in a greater number of established seedlings per acre, even though it causes greater seedling mortality than would have occurred in the absence of fire. Where slash is less abundant, protection needs may be satisfied by lighter fires that cover only parts of the surface and cause less increase in severity of site conditions. Wherever practical, slash should be left on southerly exposures; on such exposures, site conditions are so severe that if slash is removed restocking cannot be expected to occur at the rate at which it normally does on other exposures.

The treatment of the average Douglas fir cut-over area that will bring about the most satisfactory conditions for seedling establishment and at the same time abate the fire hazard appears to be broadcast burning of spots where slash is excessively heavy, supplemented with some piling and burning along routes of travel, on other places of high hazard, and on southerly exposures where it is undesirable to burn broadcast, leaving the remainder unburned. If strips or blocks of uncut timber were left at intervals on logged areas they would provide a more dependable seed supply than the scattered seed trees sometimes left and would also aid in fire protection. If, on lands in the Douglas fir region where stand and site conditions permit, clear cutting were replaced by some form of shelterwood or selection cutting, seedling losses from heat and drought would be greatly reduced and a most abundant seed supply would be provided. If the procedures described were adopted, a more rapid rate of restocking following logging would be assured.

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